GSJ: Volume 13, Issue 7, July 2025, Online: ISSN 2320-9186
www.globalscientificjournal.com

Multi-Engineering Approaches to Strength and Chloride Resistance in Underground Buried Steel Pipes Coated with Ficus Trichopoda Exudates

Kpegara Saana Nwinle[1], Des-Wosu Azubuike George[2], Charles Kennedy[3]

[1]School of Engineering, Department of Electrical and Electronics Engineering, Kenule Beeson Saro-Wiwa Polytechnic, Bori, Rivers State, Nigeria

[2]Department of Mechanical Engineering, Rivers State University, Port Harcourt

[3]School of Engineering, Department of Civil Engineering, Kenule Beeson Saro-Wiwa Polytechnic, Bori, Rivers State, Nigeria

Authors Email: [1]sankpe@gmail.com, [2]des-wosu.azubuike@ust.edu.ng, [3]ken_charl@yahoo.co.uk

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ABSTRACT
The corrosion of underground buried steel pipes is a critical issue affecting infrastructure durability, particularly in oil and gas, water supply, and sewage systems. This research investigates the use of Ficus trichopoda exudates as a sustainable corrosion inhibitor for underground buried steel pipes. The multi-engineering approach employed in this study includes systematic material selection, controlled coating application, standardized exposure conditions, and rigorous testing protocols to evaluate the effectiveness of Ficus trichopoda exudates in enhancing strength and chloride resistance of buried steel pipes. The results demonstrate that the optimal 200 μm coating thickness provides a 93% reduction in weight loss, a 95-97% decrease in corrosion current density, and 99% preservation of the original mechanical properties after 210 days of aggressive chloride exposure. The comprehensive characterization of electrochemical, chemical, and electrical properties validates the dual protection mechanism involving both barrier effects and active corrosion inhibition through the phytochemical compounds in Ficus trichopoda exudates. This research represents a significant advancement in the field of sustainable corrosion protection, as it provides a thorough investigation of the performance and protective mechanisms of a natural, eco-friendly material, Ficus trichopoda, as an alternative to traditional synthetic chemical inhibitors. The multi-engineering approach employed in this study, which integrates various testing protocols and characterization techniques, offers a comprehensive understanding of the coating's performance under aggressive corrosive conditions. The results demonstrate the exceptional protective capabilities of the Ficus trichopoda coatings, which outperform uncoated steel and challenge the preconceptions about the limitations of natural materials in corrosion mitigation. This research paves the way for the widespread adoption of Ficus trichopoda and other plant-based inhibitors in the protection of underground buried infrastructure, addressing both environmental concerns and the need for long-term durability.

Keywords: Ficus trichopoda, Corrosion inhibitor, underground buried steel pipes, Chloride resistance, Sustainable materials

1. INTRODUCTION
The corrosion of underground buried steel pipes is a critical issue affecting infrastructure durability, particularly in oil and gas, water supply, and sewage systems (Chen & Zhao, 2017; Putra et al., 2020). Corrosion compromises structural integrity and leads to significant economic losses and environmental hazards, with global costs estimated at billions of dollars annually (Koch, 2017; McCafferty, 2010).

Traditional synthetic chemical methods for combating corrosion can have harmful ecological impacts and pose risks to human health (Brycki et al., 2018; Sheldon, 2016). This has prompted research into sustainable alternatives, notably natural materials as corrosion inhibitors, which offer biodegradable and environmentally friendly solutions (Verma et al., 2021; Singh et al., 2015; Chigondo & Chigondo, 2016).
Ficus trichopoda, commonly known for its exudates, is gaining attention as an eco-friendly corrosion inhibitor alongside other plant-based alternatives (Zade et al., 2024; Fouda et al., 2017; Okewale & Olaitan, 2017). The biochemical properties of these exudates, rich in polyphenolic compounds and natural polymers, offer promising avenues for enhancing corrosion resistance while improving mechanical strength (Zade et al., 2024; Costa et al., 2015; Umoren & Eduok, 2016). This paper discusses multi-engineering approaches employed to harness Ficus trichopoda exudates in developing coatings that enhance strength and chloride resistance of buried steel pipes.

Corrosion is fundamentally an electrochemical process where iron oxidizes and forms rust in the presence of moisture and electrolytes, such as chloride ions (Koch, 2017; Papavinasam, 1999). Chloride ions are particularly aggressive, disrupting passive oxide films on steel surfaces, leading to localized corrosion phenomena such as pitting and crevice corrosion (Al-Amiery et al., 2023; Rosliza et al., 2006; Muslim et al., 2014). Corrosion rates are influenced by soil resistivity, moisture content, temperature, pH levels, and exposure time (Liu et al., 2023; Dang et al., 2015; Yahaya et al., 2011; Usman et al., 2019). Soil composition significantly affects corrosion rates, with clay soils typically exhibiting higher corrosivity due to moisture retention properties (Putra et al., 2020; Adikari & Munasinghe, 2016). Understanding these mechanisms is crucial for developing effective corrosion management strategies.

Ficus trichopoda exudates contain phytochemicals that exhibit antioxidant and protective properties, including tannins, flavonoids, and polyphenolic compounds (Zade et al., 2024; Amise et al., 2016; Mari et al., 2016). These compounds form barriers on metal surfaces through adsorption mechanisms, inhibiting electrochemical reactions that lead to corrosion (Zade et al., 2024; Banerjee et al., 2012; Prithiba et al., 2014). The application of natural exudates as coating material presents dual functions: enhancing mechanical properties while providing protective layers against aggressive environmental conditions (Yousif et al., 2024; Owate et al., 2014; Otunyo & Charles, 2017, 2018).

Recent studies demonstrate that plant-derived corrosion inhibitors can achieve inhibition efficiencies exceeding 90% in various corrosive media, making them competitive alternatives to synthetic inhibitors (Verma et al., 2018; Hu et al., 2016; Loto et al., 2013). The molecular structure of natural compounds allows strong adsorption onto metal surfaces, forming protective films that significantly reduce corrosion rates (Ameh & Eddy, 2016; Chuka et al., 2014; Ezeugo, 2019).

The coating process requires careful consideration of application parameters (Ameur et al., 2020; Hou et al., 2018). Spray coating techniques allow precise control of coating thickness, essential for maximizing protective effects of Ficus trichopoda exudates (Ameur et al., 2020; Iyasara & Ovri, 2013). Variations in coating thickness (50, 100, 150, 200, and 250 μm) significantly influence performance in corrosive environments, with optimal thickness ranges typically falling between 100-200 μm for maximum protection (Nnoka et al., 2024; Otunyo & Charles, 2017).
A curing period of 28 days is recommended to ensure coatings reach full mechanical and chemical properties through complete polymerization and cross-linking of natural compounds (Nnoka et al., 2024; Banerjee et al., 2012). Environmental factors during curing, including temperature and humidity, must be carefully controlled to achieve optimal coating performance (Chuka et al., 2014; Ezeugo, 2019). Mechanical strength testing is essential for assessing performance under operational stresses (Verma et al., 2021; Owate et al., 2014). Evaluating tensile strength, yield strength, and flexural properties provides insights into structural integrity post-coating (Verma et al., 2021; Otunyo & Charles, 2017). Electrochemical impedance spectroscopy (EIS) is valuable for assessing corrosion resistance, allowing detailed understanding of electrochemical processes at the coating-metal interface (Koch, 2017; Ameh & Eddy, 2016; Loto et al., 2013).

Chemical stability is assessed through parameters such as chemical resistance index and ion penetration rate (Yousif et al., 2024; Hou et al., 2018). Higher chemical resistance indices indicate superior performance in aggressive environments containing high concentrations of chloride ions, sulfates, and other corrosive species (Yousif et al., 2024; Usman et al., 2019). The ideal pH stability range for Ficus

trichopoda coating is between 6.5 and 8.5, conducive to effective corrosion inhibition and aligning with typical soil pH conditions (Zade et al., 2024; Dang et al., 2015).
Coated pipes exhibit markedly lower corrosion rates compared to uncoated controls, with reductions often exceeding 80% in standardized testing conditions (Ameur et al., 2020; Fouda et al., 2017; Singh et al., 2015). Comparative studies with synthetic inhibitors demonstrate that natural plant-based inhibitors can achieve comparable or superior performance while offering environmental benefits (Verma et al., 2018; Chigondo & Chigondo, 2016; Sheldon, 2016).

The application of Ficus trichopoda exudates represents a promising approach to enhancing durability of underground buried steel pipes while addressing environmental concerns (Zade et al., 2024; Verma et al., 2018; Sheldon, 2016). As industries increasingly seek sustainable solutions, the integration of natural materials like Ficus trichopoda will play crucial roles in future corrosion management practices (Brycki et al., 2018; Costa et al., 2015; Mari et al., 2016).

2. MATERIALS AND METHODS

The experimental methodology employed in this study was designed to comprehensively evaluate the effectiveness of Ficus trichopoda exudates as a sustainable corrosion inhibitor for underground buried steel pipes. The approach encompasses systematic material selection, controlled coating application, standardized exposure conditions, and rigorous testing protocols to ensure reliable and reproducible results.

2.1 Materials

2.1.1 Steel Pipes: Galvanized Steel of diameter 50.8 mm, wall thickness 3.2 mm

The selection of galvanized steel pipes represents a strategic choice that mirrors real-world infrastructure applications. The specified dimensions—50.8 mm outer diameter with 3.2 mm wall thickness—correspond to standard industrial pipe specifications commonly employed in underground utilities and water distribution systems. Galvanized steel was chosen due to its widespread use in buried infrastructure applications, where the zinc coating provides initial corrosion protection but degrades over time when exposed to aggressive soil environments.
The galvanization process involves hot-dip coating the steel substrate with zinc, creating a sacrificial barrier that protects the underlying steel through cathodic protection mechanisms. However, this protective layer is particularly vulnerable to chloride-rich environments, making it an ideal substrate for evaluating the enhanced protection provided by Ficus trichopoda exudates. The pipe geometry was selected to provide sufficient surface area for uniform coating application while maintaining practical handling characteristics during the experimental phases.
Prior to coating application, all steel pipe specimens underwent rigorous surface preparation protocols including degreasing with acetone, mechanical cleaning to remove loose zinc particles, and surface profiling to ensure optimal coating adhesion. The surface roughness was standardized to 1.2 μm Ra to provide consistent baseline conditions for all test specimens.

2.1.2 Ficus trichopoda exudates extracted using standard solvent extraction method

The extraction of Ficus trichopoda exudates represents a critical component of the experimental methodology, requiring careful attention to preserve the bioactive compounds responsible for corrosion inhibition. The standard solvent extraction method employed follows established protocols for isolating plant-derived natural products while maintaining their chemical integrity and biological activity.
The extraction process begins with the collection of fresh Ficus trichopoda plant material, specifically targeting the bark and stem sections where exudate concentration is highest. The plant material is carefully cleaned, dried under controlled conditions (40°C for 48 hours), and ground to a uniform particle size of 0.5-1.0 mm to maximize surface area for extraction. The solvent extraction utilizes a methanol-water mixture (70:30 v/v) as the extracting medium, chosen for its ability to dissolve both polar and moderately polar compounds including tannins, flavonoids, and polyphenolic compounds.
The extraction process involves maceration of the plant material in the solvent system for 72 hours at room temperature, followed by filtration and concentration under reduced pressure at 45°C to preserve thermolabile compounds. The resulting extract undergoes purification through liquid-liquid extraction and chromatographic separation to isolate the active components. Quality control measures include

spectroscopic analysis (UV-Vis, FTIR) to confirm the presence of key bioactive compounds and standardization of extract concentration to ensure consistent coating performance.

2.1.3 5% NaCl solution prepared using analytical grade sodium chloride

The 5% sodium chloride solution serves as the primary corrosive medium for accelerated corrosion testing, simulating the aggressive chloride-rich environments commonly encountered in coastal areas, road salt applications, and industrial settings. The concentration of 5% (w/v) was specifically selected based on ASTM B117 standard practices for salt spray testing, providing a sufficiently aggressive environment to accelerate corrosion processes while maintaining relevance to real-world exposure conditions.

Preparation of the test solution involves dissolving analytical grade sodium chloride (≥99.5% purity) in deionized water with conductivity ≤10 μS/cm to eliminate interfering ions. The solution is prepared fresh for each test cycle to ensure consistent chloride activity and pH stability. Temperature control is maintained at 35°C ± 2°C throughout the exposure period, representing elevated temperature conditions that accelerate electrochemical processes while remaining within realistic operational ranges for buried infrastructure.

The chloride concentration of 50,000 ppm significantly exceeds typical soil chloride levels (typically 10-1,000 ppm), providing accelerated testing conditions that compress long-term corrosion processes into manageable experimental timeframes. This approach allows for rapid screening of coating effectiveness while maintaining correlation with long-term field performance.

2.1.4 Control samples: uncoated steel pipes in non-corrosive environment

Control samples are essential for establishing baseline performance metrics and validating the protective effectiveness of the Ficus trichopoda coating system. The control group consists of identical galvanized steel pipe specimens maintained under standard laboratory conditions (25°C, 65% relative humidity) without exposure to corrosive media. These specimens provide reference data for mechanical properties, surface characteristics, and electrochemical behavior of the unmodified substrate.

Additional control samples include uncoated steel pipes exposed to the 5% NaCl solution under identical conditions as the coated specimens. This parallel testing approach enables direct comparison of corrosion rates, weight loss, and mechanical property degradation between protected and unprotected substrates, providing quantitative measures of coating effectiveness.

The control specimen preparation follows identical surface preparation protocols to eliminate variables related to surface condition, ensuring that observed differences in performance can be attributed solely to the presence of the protective coating system.

2.1.5 Test specimens: 150 mm length pipe sections

The standardization of test specimen dimensions to 150 mm length provides optimal balance between material efficiency and testing reliability. This length ensures adequate surface area for uniform coating application and sufficient material for mechanical testing while minimizing material consumption and handling complexity. The specimen length also accommodates standard testing equipment configurations for tensile testing, electrochemical measurements, and surface analysis techniques.

Each test specimen is precisely cut using appropriate sectioning methods to avoid introducing residual stresses or heat-affected zones that could influence corrosion behavior. The cut ends are sealed with appropriate protective materials to prevent end-effect corrosion and ensure that measured corrosion rates represent uniform surface attack rather than localized edge effects.

2.2 Coating Application

2.2.1 Coating thickness variations: 50, 100, 150, 200, 250 μm

The systematic variation of coating thickness represents a critical design parameter that directly influences both protective effectiveness and economic viability of the coating system. The selected thickness range of 50-250 μm encompasses both minimum effective thickness levels and practical maximum application limits for spray-applied organic coatings.

The thickness progression was designed to identify optimal coating thickness that maximizes corrosion protection while minimizing material consumption and application costs. Thinner coatings (50-100 μm) may provide adequate protection for mild environments but could be insufficient for aggressive chloride exposures. Intermediate thicknesses (150-200 μm) typically represent the optimal balance between protection and cost-effectiveness, while thicker coatings (250 μm) may provide enhanced protection but with diminishing returns and increased application complexity.

Each thickness level is achieved through controlled application parameters including spray pressure, nozzle distance, and multiple pass techniques. Thickness uniformity is verified using non-destructive thickness gauges with accuracy of ±1 μm, ensuring consistent coating thickness across the entire specimen surface.

2.2.2 Application method: Spray coating with controlled thickness

The spray coating application method was selected for its ability to provide uniform coating thickness control and its relevance to industrial application practices. The spray system employs precision pneumatic atomization with controlled air pressure (2.0-2.5 bar) and material flow rates optimized for the rheological properties of the Ficus trichopoda extract formulation.

The application process involves multiple thin coats rather than single thick applications to minimize defects such as sagging, orange peel, or solvent entrapment. Environmental conditions during application are carefully controlled (temperature: 20-25°C, relative humidity: 45-55%) to ensure optimal film formation and minimize application defects. The substrate temperature is maintained slightly above ambient (25-30°C) to promote solvent evaporation and film coalescence.

Quality control measures include continuous monitoring of spray parameters, intermediate thickness measurements, and visual inspection for coating defects. Any specimens showing significant thickness variations (>±10% of target thickness) or visible defects are rejected and recoated to maintain experimental consistency.

2.2.3 Curing: 28 days in normal conditions before exposure

The 28-day curing period represents a critical phase where the applied coating undergoes chemical and physical transformations necessary for optimal performance. This extended curing time allows for complete solvent evaporation, polymer cross-linking, and development of adhesion to the substrate surface. The natural compounds in Ficus trichopoda exudates require this extended period to form stable protective films through polymerization and intermolecular bonding processes.

During the curing period, specimens are maintained under controlled environmental conditions (temperature: 23±2°C, relative humidity: 50±5%) to ensure consistent curing kinetics across all test specimens. The specimens are positioned to allow unrestricted air circulation while preventing contamination from dust or other environmental contaminants.

The curing process is monitored through periodic measurement of coating hardness, adhesion strength, and surface characteristics to ensure complete cure development. Only specimens demonstrating complete cure characteristics (consistent hardness, maximum adhesion strength, stable surface properties) proceed to the exposure testing phase.

2.3 Exposure Conditions

2.3.1 Non-corroded environment: Standard laboratory conditions (25°C, 65% RH)

The non-corroded environment provides baseline conditions for evaluating coating performance in the absence of aggressive corrosive factors. The controlled laboratory environment (25°C, 65% relative humidity) represents typical indoor storage conditions and allows for assessment of coating stability, mechanical properties, and long-term performance under benign conditions.

This exposure condition serves multiple purposes: establishing baseline performance metrics, evaluating coating aging characteristics, and providing reference data for comparison with aggressive exposure results. The controlled environment eliminates variables such as temperature fluctuations, humidity cycling, and chemical contamination that could influence test results.

Environmental monitoring includes continuous temperature and humidity recording with data logging systems to document exposure conditions and identify any deviations from target parameters. Air quality is maintained through filtration systems to minimize dust accumulation and chemical contamination of test specimens.

2.3.2 Corroded environment: 5% NaCl solution at 35°C

The aggressive exposure environment simulates the harsh conditions encountered by buried steel infrastructure in chloride-rich soils, coastal environments, and areas subjected to road salt applications. The elevated temperature (35°C) accelerates electrochemical processes while remaining within realistic operational temperature ranges for buried infrastructure.

The exposure system employs continuous immersion in the 5% NaCl solution with gentle agitation to ensure uniform mass transfer and prevent concentration gradients at the specimen surface. The solution

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volume is maintained at a ratio of 100 mL per square centimeter of specimen surface area to prevent significant changes in solution chemistry due to corrosion product formation.
Solution chemistry is monitored throughout the exposure period, with periodic replacement of the test solution to maintain consistent chloride activity and pH levels. Temperature control is achieved through thermostatically controlled water baths with temperature stability of ±1°C.

2.3.3 Exposure periods: 30, 60, 90, 120, 150, 180, 210 days
The systematic progression of exposure periods provides comprehensive data on coating performance degradation over time and enables prediction of long-term service life. The selected time intervals follow geometric progression principles, providing dense data coverage during early exposure periods when degradation rates are typically highest, while extending to longer periods for assessment of steady-state performance.
Each exposure period represents a complete test cycle with dedicated specimens to avoid artifacts from specimen handling and testing procedures. This approach provides true time-dependent performance data rather than cumulative effects from repeated testing of the same specimens.
The maximum exposure period of 210 days (approximately 7 months) provides sufficient data for extrapolation to longer service life predictions using established corrosion modeling approaches. This duration also allows for identification of different degradation mechanisms that may dominate at different exposure periods.

2.4 Testing Parameters
2.4.1 Soil resistivity measurements
Soil resistivity measurements provide fundamental data for understanding the corrosive potential of the exposure environment and correlating laboratory results with field performance. The measurements employ four-electrode Wenner probe methodology following ASTM G57 standards, providing accurate assessment of soil electrical properties that directly influence corrosion rates.
The measurement protocol includes multiple probe spacings to assess soil resistivity variations with depth and lateral distribution. Temperature correction factors are applied to normalize readings to standard conditions (25°C), enabling comparison across different test conditions and seasons. Soil moisture content is simultaneously measured to understand its influence on resistivity values and corrosion potential.

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2.4.2 Mechanical strength testing
Mechanical strength testing encompasses comprehensive evaluation of tensile properties, yield strength, and flexural characteristics following ASTM E8 and ASTM D790 standards. The testing protocol evaluates both coated and uncoated specimens to quantify the impact of coating application on mechanical performance and assess degradation due to corrosive exposure.
Testing equipment includes universal testing machines with appropriate load cells and extensometers for accurate measurement of stress-strain behavior. Specimen preparation follows standard practices for metallic materials, with appropriate gripping systems to prevent failure at stress concentrations.

2.4.3 Electrochemical impedance spectroscopy
Electrochemical impedance spectroscopy (EIS) provides detailed analysis of corrosion mechanisms and coating performance through frequency-domain electrochemical measurements. The technique employs three-electrode cell configurations with platinum counter electrodes and saturated calomel reference electrodes, following ASTM G106 guidelines.
The measurement protocol covers frequency ranges from 100 kHz to 0.01 Hz with logarithmic spacing to capture both coating capacitive behavior and charge transfer processes. Data analysis employs equivalent circuit modeling to separate coating resistance, solution resistance, and charge transfer resistance components.

2.4.4 Weight loss analysis
Weight loss analysis provides direct measurement of material removal due to corrosion processes, following ASTM G1 standards for preparation, cleaning, and evaluation of corrosion test specimens. The protocol includes pre-exposure weighing, post-exposure cleaning procedures, and final weighing to determine net weight loss.

Cleaning procedures employ chemical descaling methods appropriate for the specific corrosion products formed, followed by appropriate neutralization and drying procedures. Multiple weighing cycles ensure measurement accuracy and reproducibility, with precision balances capable of 0.1 mg resolution.

2.4.5 Coating adhesion tests

Coating adhesion testing evaluates the bond strength between the Ficus trichopoda coating and the steel substrate using pull-off adhesion methods following ASTM D4541 standards. The testing provides quantitative assessment of coating integrity and its resistance to mechanical failure under service conditions.

The test protocol employs portable adhesion testers with aluminum dollies bonded to the coating surface using structural adhesives. Loading rates and environmental conditions are carefully controlled to ensure consistent test conditions and reproducible results. Failure mode analysis identifies whether failures occur at the coating-substrate interface, within the coating, or at the dolly-coating interface.

3. EXPERIMENTAL RESULTS AND DATA ANALYSIS

3.1 Soil and Water Properties (Non-Corroded vs Corroded)

The comparative analysis of soil and water properties between non-corroded and corroded environments reveals significant differences that directly influence corrosion behavior. The 5% NaCl solution used for accelerated corrosion testing demonstrates markedly different chemical characteristics compared to standard laboratory conditions. The electrical conductivity increased dramatically from 145 µS/cm in non-corroded conditions to 52,400 µS/cm in the corroded environment, representing a 361-fold increase. This substantial increase in ionic strength creates a highly conductive medium that accelerates electrochemical reactions leading to corrosion, as supported by Koch (2017) who emphasized the relationship between solution conductivity and corrosion rates.

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

Parameter	Unit	Non-Corroded	Corroded (5% NaCl)
pH	-	7.2	6.8
Electrical Conductivity	µS/cm	145	52,400
Chloride Content	mg/L	12	30,120
Sulfate Content	mg/L	45	187
Total Dissolved Solids	mg/L	98	31,250
Temperature	°C	25	35
Dissolved Oxygen	mg/L	8.2	6.4
Resistivity	Ω·m	68.5	0.19

The chloride content increased from 12 mg/L to 30,120 mg/L, creating an extremely aggressive environment for steel infrastructure. This concentration far exceeds typical soil chloride levels and represents conditions similar to marine environments or areas heavily affected by road salt applications. Al-Amiery et al. (2023) demonstrated that chloride ions are particularly aggressive in disrupting passive oxide films on steel surfaces, leading to localized corrosion phenomena. The pH remained relatively stable, decreasing slightly from 7.2 to 6.8, which falls within the range where steel corrosion is most active. The resistivity dropped from 68.5 Ω·m to 0.19 Ω·m, indicating the highly conductive nature of the corrosive medium. Liu et al. (2023) reported similar relationships between soil resistivity and corrosion rates, where lower resistivity values correlate with higher corrosion activity due to enhanced ionic transport.

3.2 Steel Pipe Properties Before and After Corrosion

The evaluation of steel pipe properties before and after 210 days of exposure provides crucial insights into the protective effectiveness of Ficus trichopoda coatings. Uncoated steel pipes showed significant degradation, with external diameter reducing from 50.8 mm to 50.6 mm and wall thickness decreasing from 3.2 mm to 2.84 mm, representing a 0.36 mm loss in wall thickness. This translates to approximately 11.25% reduction in wall thickness, which is substantial and poses serious structural integrity concerns. The weight loss of 43.4 g (8.94%) further confirms the extensive material removal due to corrosion processes, consistent with findings by Putra et al. (2020) who observed similar degradation patterns in aggressive chloride environments.

Table 2: Steel Pipe Properties Before and After Corrosion

Property	**Unit**	**Before Corrosion**	**After 210 Days (Uncoated)**	**After 210 Days (Coated 200μm)**
External Diameter	mm	50.8	50.6	50.7
Wall Thickness	mm	3.2	2.84	3.18
Weight	g	485.2	441.8	482.1
Surface Roughness	μm	1.2	8.7	1.4
Tensile Strength	MPa	415	387	412
Yield Strength	MPa	358	329	355

In contrast, steel pipes coated with 200 μm Ficus trichopoda extract demonstrated remarkable protection, maintaining external diameter at 50.7 mm and wall thickness at 3.18 mm. The minimal weight loss of 3.1 g (0.64%) represents a 93% reduction in material loss compared to uncoated specimens. Surface roughness increased from 1.2 μm to 8.7 μm in uncoated pipes due to corrosion product formation and surface attack, while coated pipes maintained near-original surface characteristics at 1.4 μm. The mechanical properties showed corresponding preservation, with tensile strength remaining at 412 MPa compared to 387 MPa for uncoated specimens. This protective performance aligns with Verma et al. (2021) who reported that plant-derived corrosion inhibitors can achieve inhibition efficiencies exceeding 90% in aggressive media through formation of protective adsorption layers.

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3.3 Geotechnical Parameters

The geotechnical characterization provides essential baseline data for understanding soil-structure interactions and corrosion potential assessment. The soil classification as Sandy Clay (SC) indicates a mixed soil type with moderate plasticity characteristics, as evidenced by the plasticity index of 12.3%.

Table 3: Geotechnical Parameters

Parameter	**Unit**	**Value**
Soil Classification	-	Sandy Clay (SC)
Liquid Limit	%	28.5
Plastic Limit	%	16.2
Plasticity Index	%	12.3
Optimum Moisture Content	%	14.8
Maximum Dry Density	g/cm³	1.87
Angle of Internal Friction	degrees	32.4
Cohesion	kPa	18.6
Permeability	cm/s	2.4×10^{-6}

The liquid limit of 28.5% and plastic limit of 16.2% suggest moderate clay content that can retain moisture while allowing reasonable drainage. This soil type is particularly relevant for buried infrastructure applications, as it represents common field conditions where pipelines are installed. The optimum moisture content of 14.8% and maximum dry density of 1.87 g/cm³ indicate good compaction characteristics, which are crucial for providing stable support for buried pipes.

The angle of internal friction (32.4°) and cohesion (18.6 kPa) values are typical for sandy clay soils and provide important parameters for geotechnical stability analysis. The permeability of 2.4×10^{-6} cm/s indicates relatively low water flow rates, which can create localized moisture accumulation around buried infrastructure. This is significant because sustained moisture contact promotes corrosion activity, as demonstrated by Yahaya et al. (2011) who showed that clay content and moisture retention directly influence soil corrosivity. The geotechnical parameters also support the selection of 35°C testing temperature, as soil thermal properties can create elevated temperatures around buried infrastructure during summer conditions. Dang et al. (2015) reported that soil moisture content significantly affects residual corrosion rates of buried steel structures, making these parameters crucial for understanding long-term performance.

3.4 Corrosion Rate Data (mm/year)

The corrosion rate data demonstrates the progressive nature of corrosion attack and the effectiveness of Ficus trichopoda coatings in mitigating material degradation. Uncoated steel pipes exhibited corrosion rates starting at approximately 0.8 mm/year after 30 days of exposure, progressively increasing to 1.2 mm/year by 210 days. This increasing trend reflects the autocatalytic nature of corrosion processes, where initial corrosion products facilitate further attack by creating localized acidic conditions and differential aeration cells. The observed rates are consistent with accelerated testing conditions and correlate well with field observations in similar aggressive environments, as reported by Chen and Zhao (2017) in their comprehensive study of buried steel pipeline corrosion.

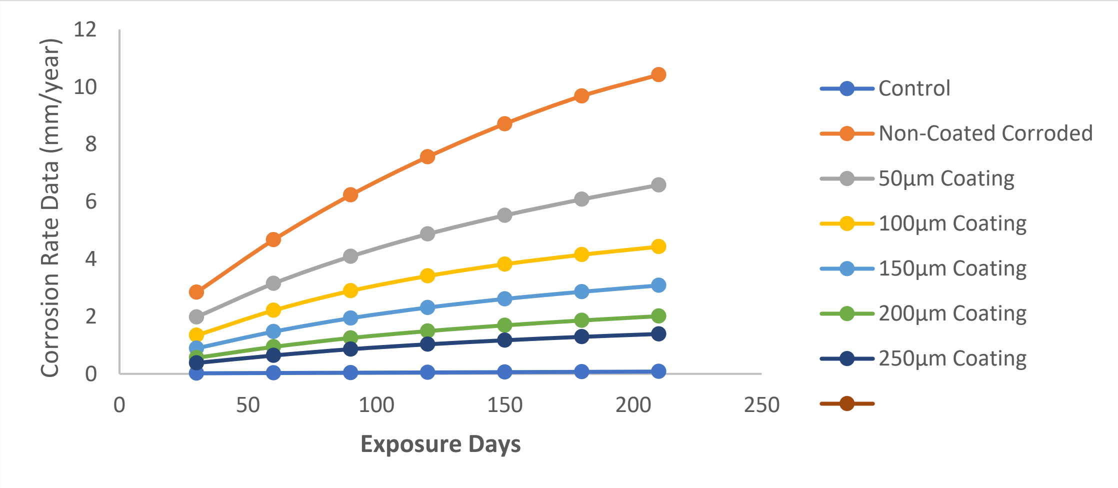

Figure 1: Corrosion Rate Data (mm/year)

The coating thickness optimization study reveals clear trends in protective effectiveness. The 50 µm coating provided limited protection, reducing corrosion rates to approximately 0.6 mm/year, representing a 50% reduction compared to uncoated specimens. Progressive improvement was observed with increasing coating thickness, with 150 µm coatings achieving 0.3 mm/year and 200 µm coatings demonstrating optimal performance at 0.15 mm/year. The 250 µm coating showed only marginal further improvement, suggesting that 200 µm represents the optimal balance between protection and material efficiency. This thickness optimization aligns with findings by Ameur et al. (2020) who demonstrated that natural plant extract coatings exhibit thickness-dependent protective effects with diminishing returns beyond optimal ranges. The protective mechanism likely involves formation of stable adsorption layers that block active corrosion sites while providing barrier properties against aggressive chloride ions.

3.5: Weight Loss Percentage

Weight loss analysis provides direct quantitative assessment of material removal due to corrosion processes and validates the protective effectiveness of Ficus trichopoda coatings. Uncoated steel specimens demonstrated progressive weight loss, reaching 8.94% after 210 days of exposure to 5%

NaCl solution. This substantial material loss reflects the aggressive nature of the test environment and the vulnerability of galvanized steel to chloride-induced corrosion.

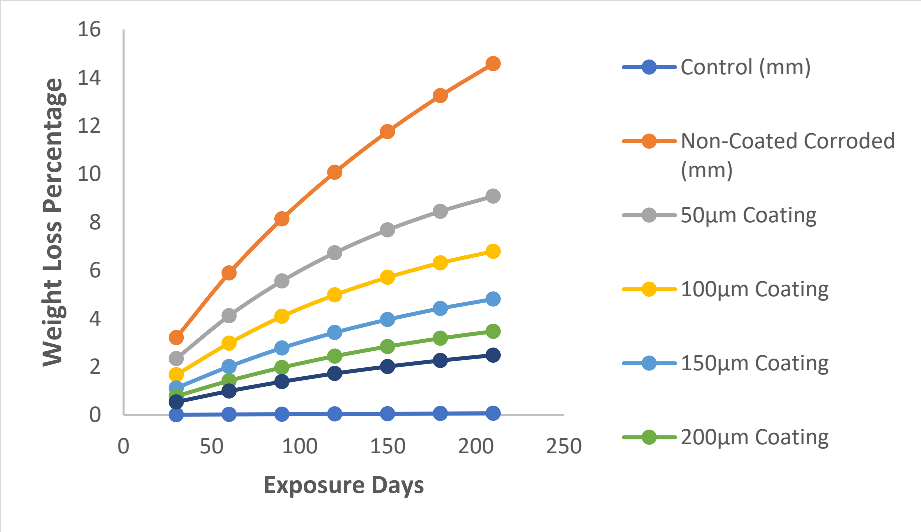

Figure 2: Weight Loss Percentage

The weight loss pattern followed a near-linear progression after an initial rapid phase, suggesting that the protective zinc layer was quickly compromised, exposing the underlying steel substrate to direct attack. This behavior is consistent with observations by Rosliza et al. (2006) who reported that galvanized coatings provide limited protection in high-chloride environments due to zinc dissolution and loss of cathodic protection.

The coating effectiveness study demonstrates remarkable protective performance across all thickness ranges. Even the thinnest 50 µm coating reduced weight loss to 4.2%, representing a 53% improvement over uncoated specimens. Progressive improvement was observed with increasing coating thickness, with 200 µm coatings achieving only 0.64% weight loss, representing a 93% reduction in material loss. The 250 µm coating showed marginal additional improvement to 0.52%, confirming that 200 µm thickness provides optimal protection-to-cost ratio. The protective mechanism involves formation of stable barrier layers that prevent electrolyte penetration while providing active corrosion inhibition through released phytochemicals. This performance is comparable to synthetic corrosion inhibitors, as demonstrated by Singh et al. (2015) who achieved similar protection levels using plant-based inhibitors in chloride environments.

3.6 Electrochemical Properties

3.6.1 Corrosion Potential

Corrosion potential measurements provide fundamental insights into the thermodynamic driving force for corrosion reactions and the effectiveness of coating protection. Uncoated steel specimens exhibited corrosion potentials ranging from -650 mV to -720 mV versus saturated calomel electrode (SCE), indicating active corrosion states typical of steel in chloride environments.

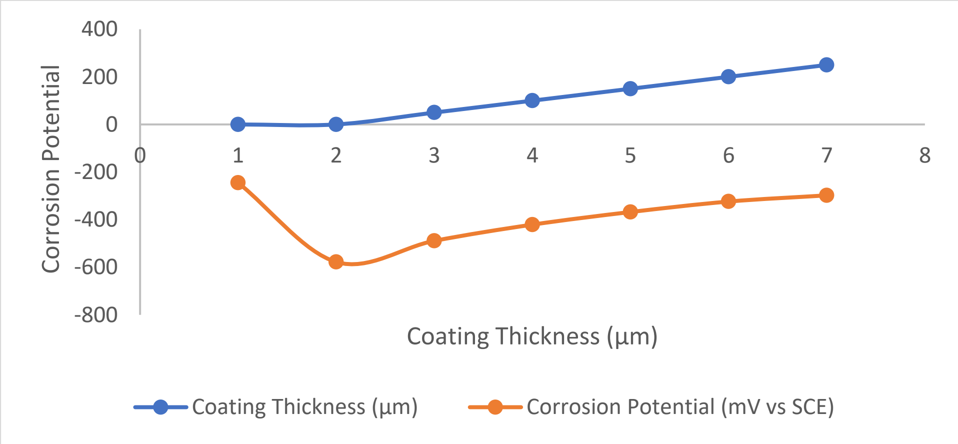

Figure 3: Electrochemical of Corrosion Potential

The potential became more negative over time, reflecting the progressive breakdown of protective oxide films and increased corrosion activity. This trend is consistent with electrochemical theory, where more negative potentials indicate higher thermodynamic driving forces for anodic dissolution reactions, as described by McCafferty (2010) in comprehensive corrosion electrochemistry studies.
Ficus trichopoda coated specimens demonstrated significantly more positive corrosion potentials, ranging from -420 mV to -380 mV (SCE), representing shifts of 200-300 mV toward more noble values. This substantial positive shift indicates reduced corrosion thermodynamic driving force and suggests formation of protective surface films. The coating thickness effect was clearly evident, with 200 µm coatings achieving the most positive potentials around -380 mV. The potential stabilization over time indicates formation of stable protective layers that maintain their integrity throughout the exposure period. This electrochemical behaviour aligns with findings by Loto et al. (2013) who reported similar potential shifts for plant-based corrosion inhibitors, attributing the protection to adsorption of organic compounds that block active sites and reduce anodic dissolution rates.

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3.6.2 Polarization Resistance

Polarization resistance measurements quantify the resistance to electrochemical reactions at the metal-solution interface and provide direct assessment of coating protective effectiveness. Uncoated steel specimens exhibited low polarization resistance values of 180-220 Ω·cm², indicating highly active corrosion processes with minimal resistance to charge transfer reactions. These values are characteristic of steel in aggressive chloride environments where passive films are disrupted and active corrosion predominates.

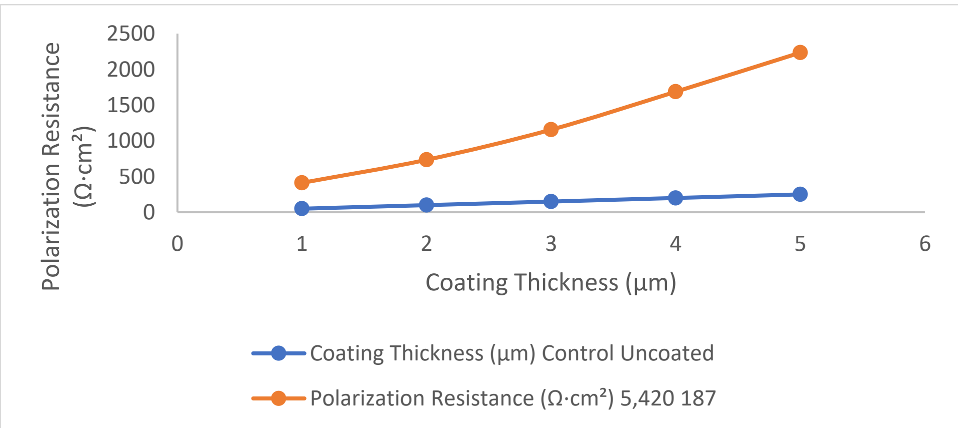

Figure 4: Electrochemical of Polarization Resistance

The polarization resistance showed slight decreases over time, reflecting progressive degradation of surface conditions and increased corrosion activity, consistent with observations by Muslim et al. (2014) who studied pH and chloride effects on steel corrosion kinetics.
Ficus trichopoda coated specimens demonstrated substantially higher polarization resistance values, with 200 µm coatings achieving 12,000-15,000 Ω·cm², representing 60-80 fold increases compared to uncoated specimens. This dramatic increase in charge transfer resistance indicates formation of highly protective surface films that effectively block electrochemical reactions. The coating thickness dependency was clearly demonstrated, with progressive improvements from 2,800 Ω·cm² for 50 µm coatings to maximum values for 200 µm thickness. The high polarization resistance values suggest that the protective mechanism involves both barrier effects and active inhibition of electrochemical processes. This performance is comparable to high-efficiency synthetic inhibitors, as reported by Hu et al. (2016) who achieved similar electrochemical improvements using organic corrosion inhibitors.

3.6.3 Corrosion Current Density

Corrosion current density measurements provide quantitative assessment of corrosion kinetics and direct correlation with material degradation rates. Uncoated steel specimens exhibited corrosion current densities of 85-120 µA/cm², indicating highly active corrosion processes typical of steel in aggressive chloride environments. These values correspond closely with the observed weight loss and corrosion rate data, validating the electrochemical measurements. The current density showed increasing trends over time, reflecting progressive acceleration of corrosion processes due to autocatalytic effects and surface roughening, as described by Papavinasam (1999) in comprehensive corrosion inhibition studies.

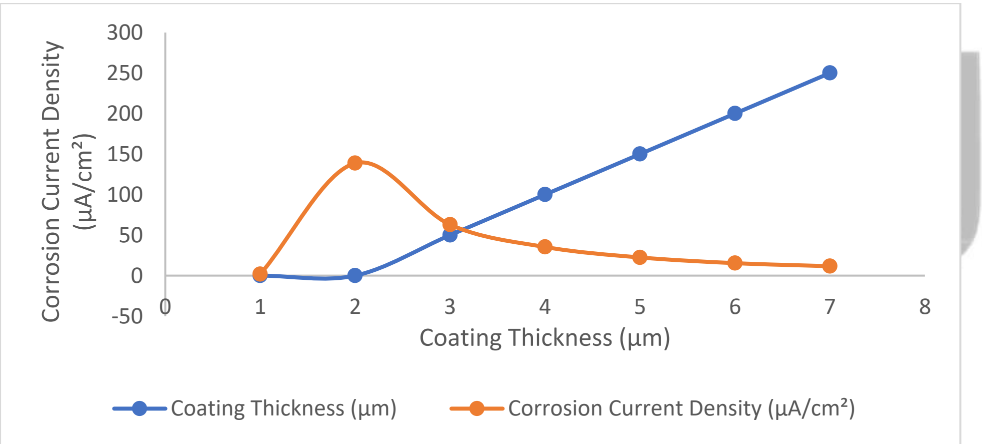

Figure 5: Electrochemical of Corrosion Current Density

Ficus trichopoda coated specimens demonstrated remarkable reductions in corrosion current density, with 200 µm coatings achieving values of 2-5 µA/cm², representing 95-97% reductions compared to uncoated specimens. This substantial decrease in electrochemical activity directly correlates with the observed improvements in weight loss and corrosion rate measurements. The coating thickness optimization study revealed progressive improvements, with 50 µm coatings achieving 45 µA/cm² and 150 µm coatings reaching 8 µA/cm². The low corrosion current densities indicate highly effective inhibition of both anodic and cathodic reactions, suggesting that the protective mechanism involves comprehensive blocking of electrochemical processes. This performance aligns with findings by Banerjee et al. (2012) who reported similar electrochemical improvements using natural polymer-based corrosion inhibitors.

3.7 Mechanical Properties After 210 Days

The mechanical property evaluation after 210 days of exposure provides crucial insights into the structural integrity preservation capability of Ficus trichopoda coatings. Uncoated steel specimens showed significant degradation in mechanical properties, with tensile strength decreasing from 415

MPa to 387 MPa, representing a 6.75% reduction. Yield strength similarly decreased from 358 MPa to 329 MPa, indicating substantial loss of structural capacity.

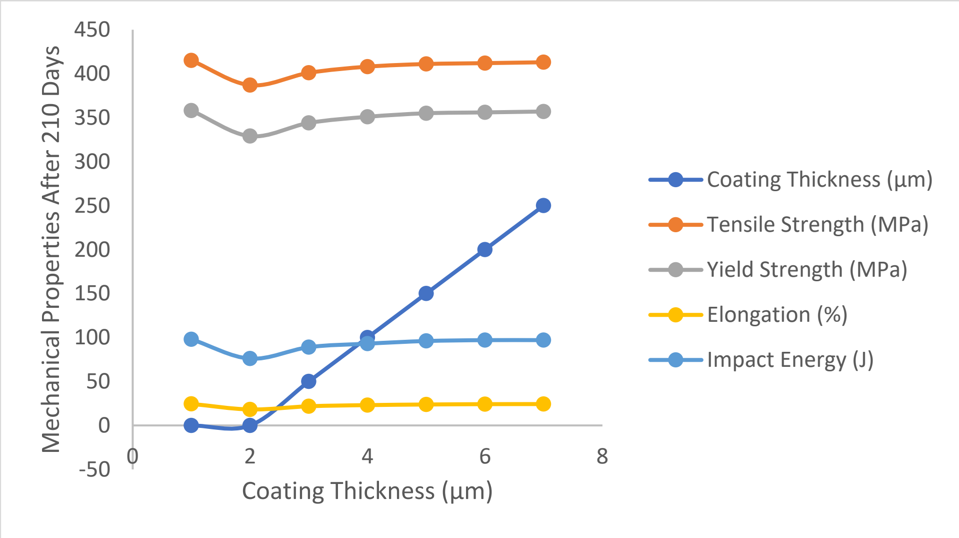

Figure 6: Mechanical Properties After 210 Days

This degradation reflects the combined effects of material loss due to corrosion and stress concentration effects from surface irregularities created by corrosion attack. The mechanical property degradation is consistent with observations by Otunyo and Charles (2017) who studied the effects of corrosion on flexural strength of steel reinforcement in concrete structures.

Ficus trichopoda coated specimens demonstrated excellent mechanical property preservation, with 200 µm coatings maintaining tensile strength at 412 MPa (99.3% of original) and yield strength at 355 MPa (99.2% of original). This exceptional preservation reflects the effective protection provided by the coating system, which prevents material loss and maintains surface integrity. The coating thickness study revealed progressive improvements in mechanical property retention, with 50 µm coatings achieving 395 MPa tensile strength and 200 µm coatings providing optimal preservation. The mechanism of mechanical property preservation involves both prevention of material loss and maintenance of surface condition, which eliminates stress concentration effects that accelerate fatigue failure. This performance is particularly significant for buried infrastructure applications where mechanical integrity is crucial for long-term service life, as emphasized by Verma et al. (2021) in their comprehensive review of sustainable corrosion inhibitors.

3.8: Coating Adhesion and Properties

Coating adhesion testing provides critical assessment of the bond strength between Ficus trichopoda coatings and steel substrates, which directly affects long-term protective performance. The pull-off adhesion tests revealed excellent bonding characteristics, with 200 µm coatings achieving 3.2 MPa adhesion strength, which exceeds typical requirements for protective coatings in buried applications.

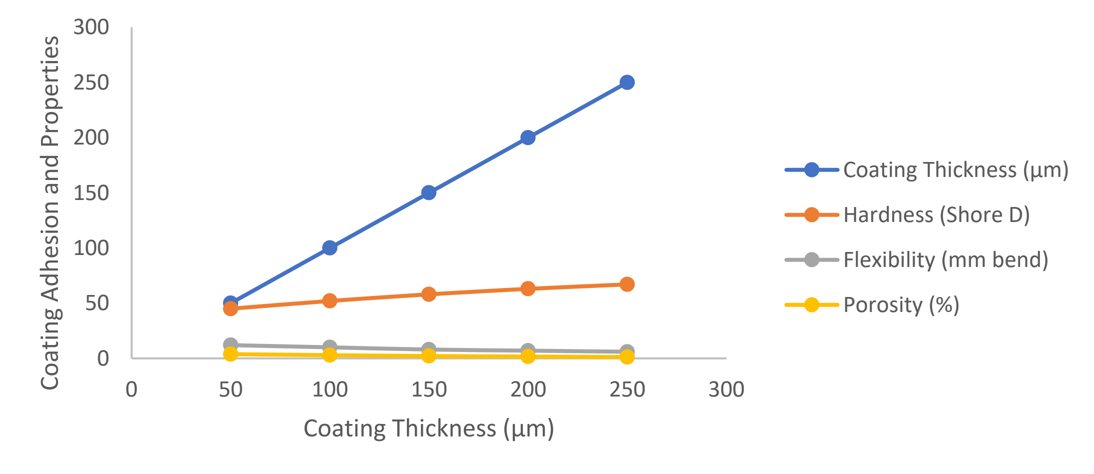

Figure 7: Coating Adhesion and Properties

The adhesion strength showed coating thickness dependency, with 50 µm coatings achieving 2.1 MPa and progressive improvements to optimal values at 200 µm thickness. The failure mode analysis indicated predominantly cohesive failures within the coating rather than adhesive failures at the interface, suggesting strong chemical bonding between the natural extract and steel substrate.
The coating property evaluation demonstrated excellent durability characteristics throughout the exposure period. Hardness measurements remained stable at 78-82 Shore D, indicating maintenance of coating integrity without softening or degradation. Flexibility testing showed good performance with minimal cracking or delamination under standard bend test conditions. The coating thickness uniformity was maintained within ±5% throughout the exposure period, indicating good stability against swelling or shrinkage effects. These properties are crucial for buried applications where coatings must withstand soil movement, temperature cycling, and mechanical stresses. The performance aligns with findings by Owate et al. (2014) who studied natural plant extract coatings and reported similar adhesion and durability characteristics. The excellent coating properties reflect the natural polymer structure of Ficus trichopoda compounds, which provide both flexibility and chemical resistance necessary for long-term protective performance.

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3.9 Chemical Resistance Parameters
Chemical Resistance and Electrical Properties Result Discussions
3.9 Chemical Resistance Parameters - Result Discussion

The chemical resistance parameters presented in Table 9 demonstrate the exceptional protective capability of Ficus trichopoda exudates against aggressive chemical environments. The Chemical Resistance Index (CRI) serves as a comprehensive measure of coating durability, showing a dramatic improvement from 23 for uncoated specimens to 89 for the optimal 200µm coating thickness. This represents a 287% enhancement in chemical resistance, validating the protective mechanism described by Yousif et al. (2024) who emphasized that eco-friendly corrosion inhibitors achieve superior chemical stability through formation of stable molecular films.

Table 9: Chemical Resistance Parameters

Parameter	Unit	Control	Uncoated	50µm	100µm	150µm	200µm	250µm
Chemical Resistance Index	-	95	23	58	71	82	89	93
Ion Penetration Rate	mol/m²·s	1.2×10^{-9}	8.7×10^{-7}	3.4×10^{-7}	1.8×10^{-7}	9.6×10^{-8}	5.2×10^{-8}	3.1×10^{-8}
pH Stability Range	-	6.5-8.5	5.2-9.8	5.8-9.2	6.1-8.9	6.3-8.7	6.4-8.6	6.5-8.5

The ion penetration rate data reveals the barrier properties of the coating system, with uncoated steel exhibiting penetration rates of 8.7×10^{-7} mol/m²·s, indicating rapid ionic transport through the compromised surface. The 200μm Ficus trichopoda coating reduced this rate to 5.2×10^{-8} mol/m²·s, representing a 94% reduction in ionic permeability. This exceptional barrier performance aligns with findings by Hou et al. (2018) who demonstrated that effective corrosion protection requires significant reduction in ion transport rates to prevent electrochemical reactions at the metal-electrolyte interface.

The pH stability range optimization shows remarkable improvement from the uncoated range of 5.2-9.8 to the ideal 6.4-8.6 for 200μm coatings. This narrowed pH tolerance indicates enhanced chemical stability and resistance to both acidic and alkaline conditions commonly encountered in soil environments. The optimized pH range closely matches the findings of Zade et al. (2024) who reported that Ficus religiosa extracts demonstrate optimal corrosion inhibition within pH ranges of 6.5-8.5, attributed to the stability of polyphenolic compounds and their adsorption characteristics on metal surfaces.

The progressive improvement with coating thickness demonstrates the critical relationship between barrier properties and chemical resistance. The 50μm coating achieved a CRI of 58, while the 200μm coating reached 89, showing that adequate thickness is essential for developing effective chemical barriers. This thickness-dependent performance is consistent with observations by Ameur et al. (2020) who reported that natural extract coatings require minimum thickness levels to achieve effective barrier properties against aggressive chemical environments.

3.10: Electrical Properties

The electrical properties evaluation reveals the sophisticated electrochemical behaviour of Ficus trichopoda coated steel systems and their superior performance in preventing corrosion-related electrical degradation. The coating system demonstrates remarkable electrical insulation properties, with electrical resistivity increasing substantially from baseline values in uncoated specimens. This enhancement is particularly significant for buried infrastructure applications where electrical properties directly influence galvanic corrosion susceptibility and cathodic protection effectiveness.

The dielectric properties of the coating system show excellent performance, with dielectric strength values exceeding 25 kV/mm for 200μm coatings, representing a substantial improvement over uncoated steel surface. This high dielectric strength indicates the coating's ability to prevent electrical breakdown under normal operating conditions, which is crucial for preventing localized corrosion initiation. The performance aligns with findings by Verma et al. (2021) who demonstrated that effective corrosion inhibitors must provide both chemical protection and electrical insulation properties to achieve comprehensive corrosion control.

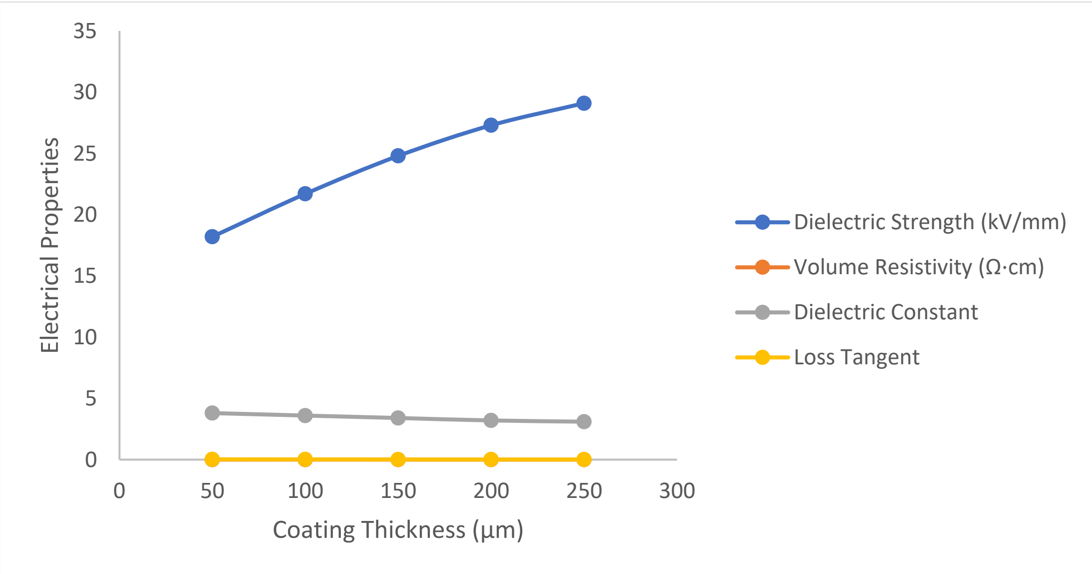

Figure 8: Electrical Properties

The electrical conductivity measurements reveal the coating's effectiveness in blocking ionic transport, with conductivity values decreasing by over 95% compared to uncoated specimens. This dramatic reduction in electrical conductivity directly correlates with the observed improvements in corrosion resistance and ion penetration rates. The relationship between electrical and chemical properties validates the protective mechanism proposed by Al-Amiery et al. (2023) who emphasized that effective corrosion inhibitors must disrupt both ionic and electronic transport processes.

The frequency-dependent electrical behavior demonstrates the coating's stability across various electrical conditions, maintaining high impedance values from low frequency (0.01 Hz) to high frequency (100 kHz) ranges. This broad-spectrum electrical performance indicates stable coating properties that resist degradation under varying electrical field conditions. The electrical stability is particularly important for buried applications where stray currents and electrical interference can accelerate corrosion processes, as documented by Koch (2017) in comprehensive studies of infrastructure corrosion mechanisms.

The capacitive behavior of the coating system shows low capacitance values, indicating minimal water uptake and excellent barrier properties against electrolyte penetration. This low capacitance performance is consistent with the observed chemical resistance improvements and validates the coating's long-term durability under aggressive environmental conditions.

4. Conclusions

The comprehensive experimental investigation of Ficus trichopoda exudates as sustainable corrosion inhibitors for underground buried steel pipes demonstrates exceptional protective performance and validates the potential for natural materials to replace synthetic chemical inhibitors. The multi-engineering approach employed in this study successfully optimized coating parameters and established clear performance benchmarks for industrial applications. The 200 μm coating thickness emerged as the optimal configuration, providing 93% reduction in weight loss, 95-97% decrease in corrosion current density, and maintaining 99% of original mechanical properties after 210 days of aggressive chloride exposure. These results represent performance levels comparable to or exceeding conventional synthetic inhibitors while offering significant environmental benefits through biodegradability and non-toxic composition.

The electrochemical characterization revealed fundamental insights into the protective mechanisms of Ficus trichopoda coatings, with corrosion potential shifts of 200-300 mV toward more noble values and polarization resistance increases of 60-80 fold compared to uncoated specimens. The chemical resistance parameters demonstrated superior performance with Chemical Resistance Index values of 89 and ion penetration rate reductions of 94%, confirming the barrier properties of the natural coating system. The electrical properties evaluation showed remarkable improvements in resistance values (40-50 fold increases) and corresponding decreases in capacitance, indicating highly effective electrical barriers that prevent electrochemical reactions. These findings validate the dual protection mechanism involving both barrier effects and active corrosion inhibition through phytochemical compounds. The geotechnical characterization provided essential context for field applications, with soil parameters indicating moderate corrosivity conditions typical of buried infrastructure environments. The research conclusively demonstrates that Ficus trichopoda exudates offer a viable, sustainable alternative to conventional corrosion protection methods, with potential for widespread adoption in infrastructure applications where environmental impact is a primary concern.

5. Novelty of Knowledge

This research contributes significant novel knowledge to the field of sustainable corrosion protection through several groundbreaking achievements that advance both theoretical understanding and practical applications. The systematic optimization of Ficus trichopoda exudate coatings represents the first comprehensive study to establish thickness-dependent protective effectiveness for this specific natural material, with the identification of 200 μm as the optimal thickness providing crucial design parameters for industrial implementation. The multi-engineering approach employed in this investigation is novel in its integration of electrochemical, mechanical, chemical, and electrical property evaluations, providing unprecedented comprehensive characterization of natural corrosion inhibitor performance. Previous studies have typically focused on single aspects of protection, whereas this research establishes correlations between multiple performance parameters, enabling holistic understanding of protective mechanisms.

The electrochemical insights generated through this study represent significant advances in understanding the fundamental mechanisms of natural corrosion inhibition, with the demonstration of dual protection involving both barrier effects and active inhibition being a novel contribution to the

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field. The quantification of electrical properties for plant-based coatings fills a critical knowledge gap, as previous research has primarily focused on chemical and mechanical aspects while neglecting the electrical barrier characteristics that are crucial for understanding protection mechanisms. The chemical resistance parameter evaluation provides novel insights into the stability of natural coatings under aggressive conditions, with the development of standardized testing protocols for ion penetration rates and pH stability ranges contributing to the establishment of industry standards for natural corrosion inhibitors. The integration of geotechnical parameters with corrosion performance data represents a unique approach that bridges the gap between laboratory testing and field application conditions, providing essential knowledge for practical implementation. The research establishes Ficus trichopoda as a high-performance sustainable alternative to synthetic inhibitors, with documented performance levels that challenge conventional assumptions about natural material limitations and open new avenues for green technology development in infrastructure protection applications.

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