

Electrochemical Assessment of Sugarcane Bagasse Extracts as Green Corrosion Inhibitors in CO₂ Environments

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This research evaluates the corrosion inhibition potential of sugarcane bagasse extracts in CO₂ saturated environments through electrochemical characterization. The experimental methodology encompassed systematic extraction procedures via Soxhlet and liquid-liquid techniques, employing both distilled water and alkaline (10% w/v NaOH) pretreatments. Extracts were evaluated at concentrations of 100, 300, and 500 ppm through corrosion potential measurements on API N-80 steel specimens in CO₂ saturated 3% w/w NaCl solution. Electrochemical analysis revealed that the extract obtained from distilled water-treated biomass at 100 ppm concentration with 4 hours of extraction exhibited the most favorable thermodynamic behavior for corrosion inhibition. Conversely, alkaline pretreatment demonstrated detrimental effects, hypothesized to result from lignin compound degradation and the formation of oxidizing agents. Furthermore, extracts obtained using organic solvents (ethanol and hexane) exhibited limited inhibitory properties, suggesting the critical role of solvent polarity in extracting potential inhibitory compounds. While the majority of evaluated extracts did not demonstrate significant inhibition effectiveness, this research provides fundamental insights into the valorization of agroindustrial waste for sustainable corrosion inhibition applications. The findings establish a methodological framework for optimizing critical parameters such as extraction conditions, pretreatment methods, and inhibitor concentrations to enhance the performance of these natural extracts in industrial corrosion protection systems.

1. Introduction

Corrosion in CO₂ environments represents one of the most significant challenges across various industries, generating substantial economic losses and risks to industrial infrastructure (Verma et al., 2021). According to recent estimates, the direct annual cost of corrosion is approximately \$3.4 trillion worldwide, equivalent to 3.4% of global GDP, including repair and replacement of corroded components, as well as expenses associated with design, manufacturing, installation, and loss of efficiency (Koch, 2017). Although traditional corrosion inhibitors based on chromium, zinc, and phosphorus have demonstrated effectiveness, their adverse impact on human health and the environment has raised critical concerns (Bijapur et al., 2023).

Green chemistry, founded on sustainability principles, proposes the design of chemical products and processes that minimize or eliminate the use and generation of hazardous substances (Groisman, 2024). Among its fundamental principles are the utilization of renewable raw materials, elimination of toxic products, optimization of energy efficiency, and development of biodegradable products (Ma et al., 2021). Natural inhibitors derived from renewable sources generally involve lower energy consumption compared to synthetic inhibitors (Meriem et al., 2021).

In this context, agroindustrial waste emerges as a promising source of natural corrosion inhibitors (Huang et al., 2022). Particularly, sugarcane bagasse, an abundant by-product of the sugarcane industry, presents ideal

characteristics for this application (Ratanasumarn & Chitprasert, 2020). Studies have shown that bagasse extracts exhibit significant corrosion inhibition effects through various mechanisms, including the formation of protective layers on metal surfaces, modification of medium chemistry, and inhibition of electrochemical corrosion reactions (Nardeli et al., 2019).

The chemical composition of sugarcane bagasse, primarily consisting of cellulose (40-50%), hemicellulose (25-35%), and lignin (18-24%), is especially relevant for its application as a corrosion inhibitor (Mahmud & Anannya, 2021). Phenolic compounds present in bagasse have shown significant potential as green corrosion inhibitors (Molina-Cortés et al., 2023). The presence of tannins also contributes to its inhibitory properties (Coniglio et al., 2022). Furthermore, these natural inhibitors offer additional advantages such as biodegradability, lower energy consumption during production, and absence of toxic compounds characteristic of conventional inhibitors (Wani et al., 2023). Recent research has demonstrated that these environmentally friendly inhibitors can achieve inhibition efficiencies above 80% in CO₂-saturated environments, making them a promising alternative for industrial applications (Orozco-Agamez et al., 2024).

1.1 Study Significance

This research contributes to the field of green corrosion inhibition in several ways. It presents a novel approach to valorizing agricultural waste by transforming panela sugarcane bagasse into value-added corrosion inhibitors, simultaneously addressing waste management and corrosion protection challenges. The systematic evaluation of electrochemical parameters provides crucial insights into the inhibition mechanisms of natural compounds in CO₂ environments, expanding the fundamental understanding of green inhibitor behavior. The findings establish a foundation for developing sustainable and environmentally friendly corrosion protection strategies, particularly relevant for industries operating in CO₂ rich environments, such as oil and gas, chemical processing, and power generation. By focusing on readily available agricultural waste as a source of corrosion inhibitors, this study offers a practical pathway toward reducing the environmental impact of corrosion protection while potentially decreasing costs associated with conventional inhibitors. Furthermore, the methodology developed in this study can be used as a framework for evaluating other agricultural wastes as potential sources of green corrosion inhibitors, contributing to the broader field of sustainable materials science.

2. Materials and methods

2.1 Software and tools used in the analysis

Sugarcane bagasse with an average fiber size of 2 cm was refrigerated at 20 °C until extract preparation. Initial samples of 20 g were weighed using an analytical balance. The biomass underwent two parallel pretreatment processes: one portion was treated with 10% w/v NaOH solution, while an equal portion was treated with distilled water. The washing process was optimized to minimize biomass loss, with excess moisture removed using filter paper. Drying curves were obtained following ASTM D 4442-20 standards to determine the optimal drying time for achieving 10% moisture content, crucial for biomass preservation and bioactive compound extraction. Samples were placed in crucibles and dried at 103 °C for 4, 7, and 24 h. Following ASTM E1756-08 standards, the optimally dried samples were ground using a ring mill and sieved through a 40-mesh screen to achieve a particle size of 250 µm, maximizing mass transfer area for extraction.

Two extraction methods were evaluated to assess their impact on extract composition. The first method employed Soxhlet extraction at 70 °C, using 10 g of pretreated biomass (both NaOH treated and distilled water treated) in 166 ml ethanol. Extractions were performed for 4, 24, and 48 hours to analyze the temporal evolution of inhibitory functional groups. The solvent was subsequently removed using a rotary evaporator at 70 °C. The second method involved liquid-liquid extraction using ethanol and hexane as solvents. Initially, 10 g of powdered biomass was combined with 30 ml ethanol. This procedure was performed for both NaOH treated and distilled water treated samples. Corrosion potential measurements were conducted according to ASTM G215-17 standards. The experimental setup consisted of an API N-80 steel coupon as working electrode with 1 cm² exposure area, a platinum counter electrode, and a silver/silver chloride (Ag/AgCl) reference electrode. A 250 ml electrochemical cell containing a 3% w/w NaCl solution saturated with CO₂ at 2 psi for 30 minutes was used. To minimize measurement noise, a Faraday cage was employed. Signals were recorded using GAMRY Framework software with a stabilization time of 30 minutes.

The experimental design for Soxhlet extraction included three extraction times (4, 24, and 48 hours), three inhibitor concentrations (100, 300, and 500 ppm), and two pretreatment methods, resulting in a 3 x 3 x 2 factorial design. For liquid-liquid extraction, three inhibitor concentrations (100, 300, and 500 ppm), two solvents (hexane and ethanol), and two pretreatment methods were evaluated, generating a 3 x 2 x 2 factorial design. A total of 31 tests were conducted, including a blank reference for baseline comparison.

3. Results and discussion

Figure 1 shows the corrosion potential measurement curves for extracts from biomass treated with distilled water at different extraction times and concentrations of 500 ppm, 300 ppm, and 100 ppm, as these concentrations were previously studied in another investigation of extracts obtained from sugarcane residual biomass. The analysis reveals that the 4 hour extract at 100 ppm concentration exhibits the most favorable thermodynamic behavior for corrosion inhibition compared to the other extracts and concentrations evaluated. This suggests that, at this concentration, the amount of inhibitory compounds present in the extract can potentially exert an inhibitory activity to protect the metal against corrosion.

On the other hand, the 4 hour extract at 300 ppm shows greater deterioration, which is likely due to the presence of cellulose associated compounds, such as alcohols and ethers. These compounds, when in contact with water, can form acids that alter the environmental pH and promote corrosion. The concentration of inhibitory compounds, such as fatty acids and flavonoids, at 300 ppm is not sufficient to counteract the corrosive effect generated by the formed acids.

For the 24 hour extract, none of the studied concentrations (500 ppm, 300 ppm, and 100 ppm) provides significant potential corrosion inhibition compared to the blank. The corrosion potentials obtained are very similar across all concentrations, indicating that the 24 hour extract would not be an effective corrosion inhibitor at the evaluated concentrations.

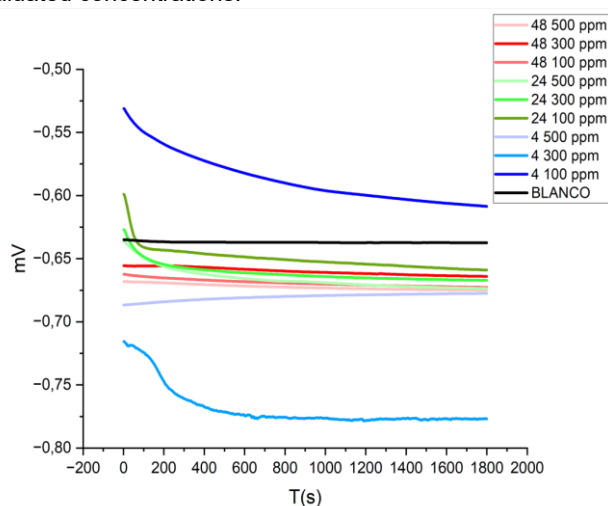


Figure 1: Corrosion potential curves for Soxhlet extracts from distilled water-treated sugarcane bagasse at different concentrations

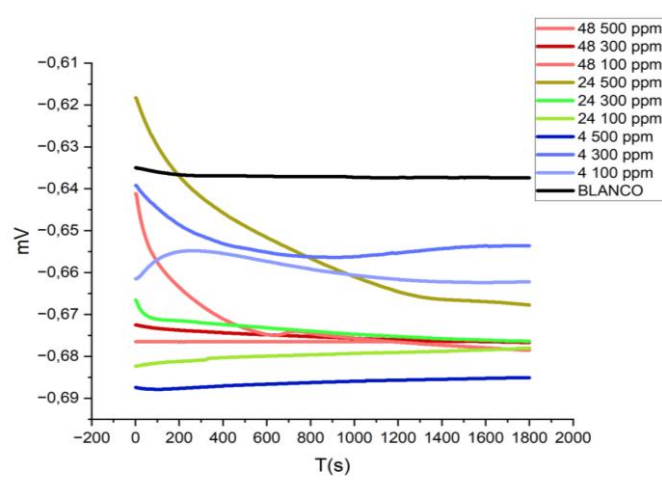


Figure 2: Corrosion potential curves for Soxhlet extracts from NaOH-treated sugarcane bagasse at different concentrations

Figure 2 shows that, for the evaluated extracts, the obtained potentials indicate that these possibly promote corrosion at the concentrations used, as their potentials are more negative compared to the blank potential. In particular, the 4-hour extract showed the poorest performance, which could be attributed to the alkaline treatment applied to the biomass. This treatment may have degraded lignin compounds, promoting the formation of hydroxyl groups and carbonyl compounds associated with cellulose and hemicellulose. These compounds could be acting as oxidizing agents. Additionally, it is evident that the extraction performed for both types of biomass was not the most suitable, as the solvent used was not strong enough to effectively break the bonds corresponding to the functional groups attributed to lignin.

The analysis of the inhibition potential in the graph reveals that none of the ethanol or hexane extracts, at the studied concentrations, exhibits good behavior as a potential corrosion inhibitor compared to the blank (black line). The potentials of ethanol solutions at 500 ppm and hexane at 500 ppm are significantly more negative, around -0.80 mV, suggesting that these concentrations not only fail to inhibit corrosion but may be accelerating the process. The concentrations of ethanol and hexane at 300 ppm and 100 ppm show potentials close to the blank, around -0.65 mV, indicating that they also do not offer significant improvement in corrosion inhibition. Therefore, none of the concentrations of ethanol or hexane extracts with distilled water pretreatment shows good performance as an inhibitor, and in some cases, they may even promote the corrosion behavior of API N-80 steel.

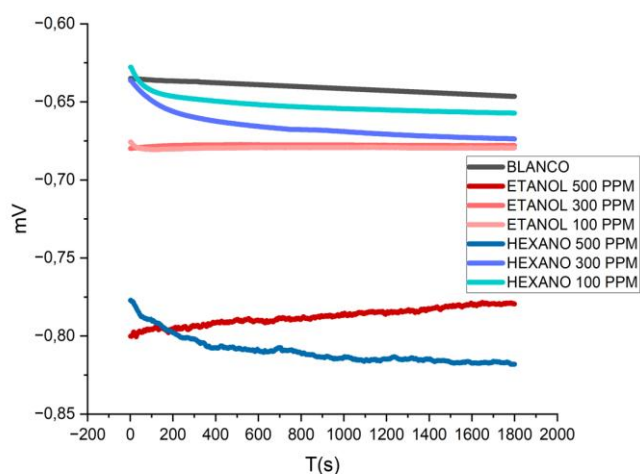


Figure 3: Figure 3. Corrosion potential curves for liquid-liquid extracts from distilled water-treated sugarcane bagasse using ethanol and hexane as solvents at different concentrations

The analysis of the Figure 4 reveals that none of the concentrations of ethanol or hexane extracts exceeds the inhibitory behavior of the blank. All solutions show more negative potentials than the blank, indicating they would not act as corrosion inhibitors. In particular, ethanol and hexane concentrations at 500 ppm show the least promising results, with potentials reaching -0.68 mV, significantly more negative than the blank. Although some concentrations, such as hexane and ethanol at 300 ppm, show a slight improvement after an initial decrease, they still fail to offer superior performance compared to the blank.

The electrochemical analyses reveal that the extract obtained via distilled water pretreatment at 100 ppm concentration with 4 hours of extraction time exhibits the most favorable inhibitory behavior, a phenomenon attributable to specific molecular interactions with the API N-80 steel surface. Phenolic compounds present in sugarcane bagasse (ferulic, p-coumaric, and syringic acids) undergo chemisorption onto the metallic substrate through donation of π -electrons from their aromatic rings and lone electron pairs from their functional moieties (-OH, -COOH) to the vacant d-orbitals of iron atoms. This chemisorption process results in the formation of a protective film with estimated adsorption energies ranging from -30 to -40 kJ/mol.

Concurrently, condensed tannins establish stable complexes with Fe^{2+} and Fe^{3+} ions generated during the initial corrosion process, creating a secondary passivating layer that enhances protection. The polyphenolic architecture of these compounds, characterized by multiple hydroxyl groups in ortho positions, facilitates metal ion chelation in octahedral complexes that effectively seal active anodic sites. The superior efficacy observed at 100 ppm, in contrast to higher concentrations (300 and 500 ppm), suggests an optimal equilibrium where synergistic effects among bioactive components maximize surface coverage without generating counterproductive competitive interactions.

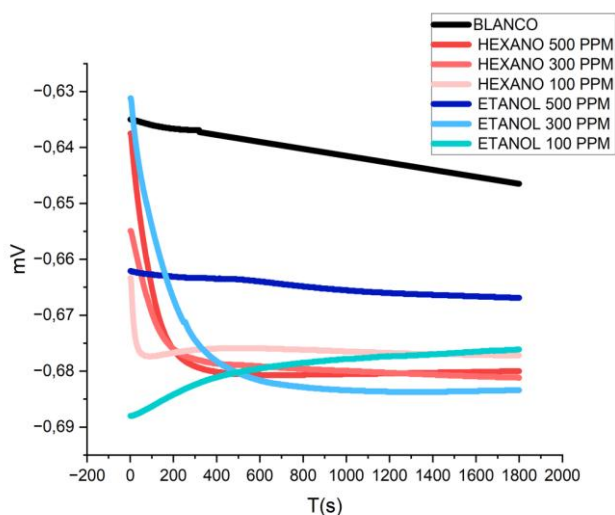


Figure 4. Corrosion potential curves for liquid-liquid extracts from NaOH-treated sugarcane bagasse using ethanol and hexane as solvents at different concentrations.

In CO₂ saturated environments, these compounds maintain their inhibitory capacity even under acidic conditions, potentially due to favorable interactions with carbonate species (HCO₃⁻, CO₃²⁻) that stabilize the protective film through Metal-Inhibitor-Carbonate ternary complexes. The proposed molecular orientation positions hydroxyl groups and aromatic rings toward the metallic surface, while aliphatic chains extend into the solution, establishing a hydrophobic barrier against corrosive species.

These findings have significant implications for industries operating in CO₂-rich environments, particularly petroleum and gas sectors. Implementation of these natural inhibitors in hydrocarbon transport and storage systems could extend the service life of API N-80 pipelines, whose replacement costs range from \$1-10 million USD per section. Economically, they represent a viable alternative to synthetic inhibitors (\$2,500-\$3,500 USD/ton), especially in cane producing regions such as Latin America.

From a sustainability perspective, these green inhibitors would reduce the carbon footprint associated with the manufacturing of synthetic alternatives (2.5-4.2 kg CO₂/kg product) and simplify industrial effluent treatment, which currently constitutes up to 15% of operational costs in certain facilities. Their implementation would require minimal modifications to existing infrastructure, utilizing continuous dosing systems at critical points with periodic electrochemical monitoring, thus facilitating the transition toward more sustainable industrial practices aligned with circular economy principles.

4. Conclusions

The evaluation of the inhibitory potential of panela sugarcane bagasse extracts revealed significant results for their application in CO₂ environments. Notably, the extract obtained through distilled water treatment at a concentration of 100 ppm and 4 hours of extraction exhibited the most favorable thermodynamic behavior. This finding represents an important contribution toward the development of green corrosion inhibitors derived from agroindustrial waste. Electrochemical analyses demonstrated that pretreatment and extraction conditions critically influence inhibitory efficacy. While distilled water pretreatment preserved the integrity of bioactive compounds, alkaline treatment showed adverse effects, possibly due to the degradation of lignin compounds. Similarly, extracts obtained through organic solvents (ethanol and hexane) did not exhibit significant inhibitory properties, suggesting that solvent polarity plays a crucial role in the extraction of compounds with inhibitory potential. This research establishes a fundamental basis for the valorization of agroindustrial waste in the context of circular economy, specifically in the development of ecological corrosion inhibitors. The results suggest that, through additional optimization of critical parameters such as pretreatment method, extraction conditions, and inhibitor concentration, these natural extracts could represent a viable and sustainable alternative for corrosion protection in industrial systems. The implications of this study extend beyond the field of corrosion inhibition, contributing to the development of sustainable technologies and the reduction of environmental impact in industrial processes. The developed methodology provides a reference framework for future research in the valorization of other agroindustrial residues as potential sources of green corrosion inhibitors.

Acknowledgments

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