An Approach to Green Corrosion Inhibitors in Acid Mine Drainage (AMD)

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Abstract

Corrosion of metals and alloys represents a significant economic burden, accounting for approximately 3–4% of the annual GDP in developed countries, according to the European Commission. Among the various forms of corrosion, one of particular concern is that caused by acid mine drainage (AMD). Due to the thermodynamic instability of metals submerged in water, corrosion is inevitable. This phenomenon becomes even more critical in AMD-affected environments, where low pH and dissolved ions accelerate material degradation. Therefore, developing sustainable and cost-effective methods to mitigate AMD-induced corrosion is essential.

This study investigates the effectiveness of a green corrosion inhibitor derived from spent coffee grounds, in reducing the corrosion rate of mild steel exposed to AMD. The primary goal is to explore a low-cost, eco-friendly alternative to conventional inhibitors, aiming to enhance the durability of metallic infrastructure in mining and industrial settings. The research methodology involves weight-loss analysis of mild steel samples immersed in AMD, with and without the green inhibitor, to quantify its protective effect.

The results demonstrate a significant reduction in material degradation when the inhibitor is present, as it forms a protective film that shields the metal from direct interaction with the acidic environment. Compared to untreated samples, the inhibited specimens show a substantial decrease in weight loss, indicating improved corrosion resistance. This protective layer, attributed to organic compounds in the coffee waste, acts as a barrier against aggressive ions in AMD.

The findings of this study highlight the potential of waste-derived inhibitors as a viable solution for mitigating AMD-related corrosion. The practical implications extend to mining operations and industrial facilities where metallic structures and machinery are at risk of premature failure due to corrosive conditions. By enhancing the service life of steel components, this research contributes to reducing maintenance costs and promoting sustainable waste management practices.

This work underscores the feasibility of using green inhibitors for corrosion protection, paving the way for further exploration of organic waste-based solutions in industrial applications.

Keywords: Corrosion, steel, AMD, green inhibitors.

Introduction

Corrosion is a widespread problem that affects the durability of metal structures, leading to economic losses of 3–4% of the annual GDP in developed countries (Kumari *et al.*, 2025). Among the various forms of corrosion, one of the most severe is acid mine drainage (AMD)-induced corrosion, which occurs in mining environments where sulfide mineral oxidation generates acidic waters rich in sulfate and metal ions [09]. This low-pH environment significantly accelerates the degradation of metallic infrastructure, particularly mild steel, commonly used in industrial and mining applications (Miguel Sarmiento *et al.*, 2024).

To promote a corrosive process, it is mandatory the formation of an electrochemical cell which is composed of an anodic zone, a cathodic zone, an electrolyte and a metal (Jares Salguero *et al.*, 2024b). In a corrosion process, usually, the anodic reaction is the one show in Equation 1 (M is the corroded metal specie). However, the most common cathodic reactions (Eq. 2 aerated neutral or alkaline aqueous medium, Eq. 3 acid aerated aqueous medium, Eq. 4 acid medium) depends on the environmental conditions which are dependent on the pH (Pancorbo, 2010).

(Eq. 1) $M \leftrightarrow M^{n+} + ne^-$

(Eq. 2) $O_2 + H_2O + 4e^- \rightarrow 4OH^-$

(Eq. 3) $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

(Eq. 4) $2H^+ + 2e^- \rightarrow H^2$

AMD is primarily caused by the oxidation of pyrite (FeS_2) in the presence of water and oxygen, leading to the formation of sulfuric acid and dissolved metal ions (Younger *et al.*, 2002):

(Eq. 5) $2FeS_2 + 7O_2 + 2H_2O \rightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+$

These aggressive conditions promote pitting corrosion, stress corrosion cracking, and material failure in industrial equipment (Miguel Sarmiento *et al.*, 2024). Studies show that mild steel exposed to AMD experiences significant weight loss and tensile strength reduction, which can lead to catastrophic failures in mining infrastructure (Miguel Sarmiento *et al.*, 2024). Given the high economic and environmental costs, developing effective corrosion mitigation strategies is crucial (Ling *et al.*, 2024).

Given the highly corrosive nature of AMD environments, effective mitigation strategies are crucial. Traditionally, inorganic inhibitors such as chromates and phosphates have been widely used. However, due to their toxicity and environmental impact, regulatory restrictions have increase and research has shifted toward green alternatives, particularly plant-derived inhibitors (Kharbouch *et al.*, 2024). Organic inhibitors, including quinolinium derivatives and imidazole-based compounds, function by adsorbing onto metal surfaces and forming a protective barrier [11]. However, their high cost and potential bioaccumulation have driven interest toward green corrosion inhibitors derived from sustainable sources (Parangusan *et al.*, 2024).

Plant-based inhibitors have emerged as a promising alternative due to their biodegradability, low toxicity, and cost-effectiveness (Mungwari *et al.*, 2024). Many natural inhibitors contain polyphenols, flavonoids, and alkaloids, which adsorb onto metal surfaces and reduce corrosion rates (Mungwari *et al.*, 2024). Among biomass-based inhibitors, spent coffee grounds (SCG) have shown significant potential due to their high polyphenol and melanoidin content, which facilitates the formation of a protective film on mild steel (Elhady *et al.*, 2024).

Electrochemical studies demonstrate that coffee waste extracts can achieve up to 96% inhibition efficiency in acidic environments. Tafel polarization and electrochemical impedance spectroscopy (EIS) tests confirm that coffee waste reduces the double-layer capacitance (Cdl) and increases charge transfer resistance (Rct), indicating strong adsorption on the metal surface. Furthermore, using coffee waste as an inhibitor aligns with circular economy principles, reducing industrial waste while providing a low-cost corrosion control method (Elhady *et al.*, 2024).

This study evaluates the corrosion inhibition efficiency of coffee waste extract in AMD environments, identifying and evaluating its protective efficiency. By assessing weight-loss measurements, electrochemical behaviour, and inhibitor-film formation, this research aims to provide a sustainable alternative to conventional inhibitors, extending the lifespan of metallic structures in mining and industrial applications.

Materials and methods

In this study carbon steel coupons with the same composition and from the same piece were prepared. Those coupons were mechanically cut into 25 mm × 25 mm × 0.75 mm (±1). Then, they were polished with silicon carbide emery papers and commercial sandpapers of different granulometry, after cleaned with distilled water and finally dried in an airflow.

Based on earlier used procedures (Cordeiro *et al.*, 2018; Elhady *et al.*, 2024; Jares Salguero *et al.*, 2024a; Ramos *et al.*, 2019; Torres *et al.*, 2011), the extraction of spent coffee was used to perform the experiments. Aqueous extract of spent coffee was obtained by infusion method.

The present investigation was carried out using commercial coffee which was used for conventional extraction in an electric coffee maker. After the extraction, it is performed a re-extraction process harnessing 200mL of distilled water for each 100g of spent coffee. The infusion method involves boiling the coffee for 10 minutes, followed by filtration through a commercial coffee filter. Finally, the second and definitive aqueous extract is filtered with a Whatman filter of 20-25 µm.

***Table 1** Characterization of the Sao Domingos AMD.*

Parameter	Value
H	2,3
Al	241.000 µg/L
As	1.090 µg/L
Cu	25.700 µg/L
Fe	214 mg/L
Hg	<0,05 µg/L
Mg	86,8 mg/L
Mn	12.850 µg/L
Ni	512 µg/L
Pb	39,9 µg/L
U	6,22 µg/L

The extracts of spent coffee grounds were used as corrosion inhibitors for carbon steel in a Sao Domingos AMD. The sample was taken at the following coordinates: 631823 X, 4169012 Y.

Triplicate carbon steel coupons were fully immersed in the São Domingos AMD in the absence and presence of the green corrosion inhibitor based in aqueous spent coffee extracts at room temperature (20±2°C). The samples were placed in a static environment without agitation. For the experiment, they are prepared three borosilicate vessels with only 50 ml of the Sao Domingos AMD and other three additional borosilicate vessels with a solution prepared with 50 ml of AMD and 5 ml of green inhibitor. It should be noted thar the pH after the inhibitor addition does not vary, thus, the pH of both solution remains in 2,3.

Weight loss was determined using a scale with an accuracy of 0,02 mg. The efficiency of the inhibitor is determined by the following expression (Torres *et al.*, 2011):

(Eq. 6) $$E\,[\%] = \frac{W_0 - W_i}{W_0}$$

Where W_0 and W_i are the weight loss in the absence and inhibitor presence respectively.

In order to evaluate significant figures, the mean of the three results obtained is the value used for the representation of each result.

Results

Fig. 2 presents the variation in corrosion rate for steel coupons exposed to AMD, with and without the inhibitor, over different immersion times. Under identical electrolyte conditions and exposure times, the spent coffee extracts form a protective layer, reducing the corrosion rate. (R_{corr}).

However, experimental data indicate that as exposure time increases, the corrosion inhibitor's efficiency decreases substantially. This fact indicates that the passivation layer form over the metallic surface is degraded over time. This result suggests that, for a real AMD a dispenser could be recommended.

Furthermore, the SEM images support the thesis of the efficiency reduction by time. As it is shown in Fig. 3, the presence of oxides over the metallic surface is similar for both samples.

Figure 1 Experimental extraction and set-up.

Conclusion

The efficiency of aqueous spent coffee extracts is proven by different researchers for acidic solutions (Cordeiro *et al.*, 2018; Elhady *et al.*, 2024; Jares Salguero *et al.*, 2024a; Ramos *et al.*, 2019; Torres *et al.*, 2011), however, this investigation evidenced it's performance in an AMD environment. This inhibition action is attributed to the blocking action of the protective layer form by the spent coffee extract. Moreover, the inhibition efficiency decreases with increasing the exposure time.

For further research, it is advisable to repeat the current experiment simulating an AMD flow and dosing the coffee extract periodically in order to avoid the efficiency decrease due to the passage of time.

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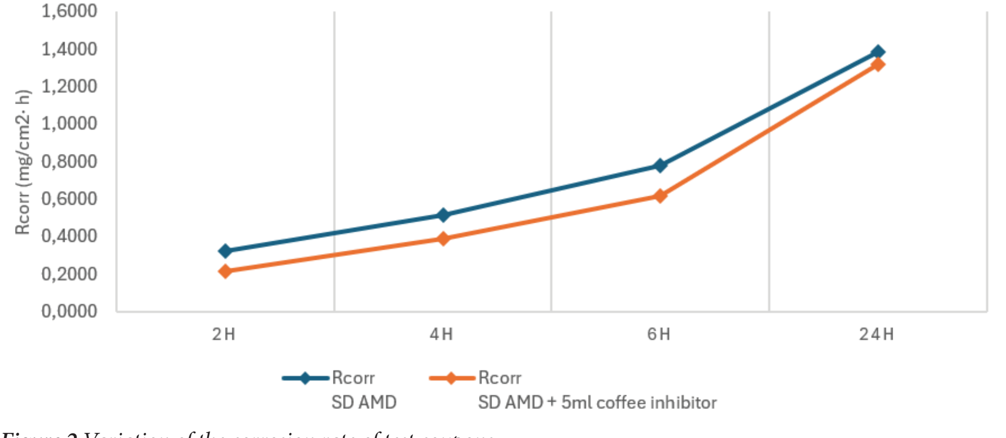

Figure 2 Variation of the corrosion rate of test coupons.

Table 2 *Variation of the corrosion rate of test coupons.*

Elapsed time and electrolyte h	R_{corr} $mg \cdot cm^{-2} \cdot h^{-1}$	R_corr SD AMD + inhibitor $mg \cdot cm^{-2} \cdot h^{-1}$
2	0,3227	0,2187
4	0,5147	0,3920
6	0,7787	0,6160
24	1,3840	1,3200

Table 3 *Inhibitor efficiency at 2, 4, 6 and 24 hours.*

Elapsed time and electrolyte	R_{corr} $mg \cdot cm^{-2} \cdot h^{-1}$	Efficiency (E) %
SD AMD, 2h	0,3227	–
SD AMD + 5 ml inhibitor, 2h	0,2187	32,2
SD AMD, 4h	0,5147	–
SD AMD + 5 ml inhibitor, 4h	0,3920	23,8
SD AMD, 6h	0,7787	–
SD AMD + 5 ml inhibitor, 6h	0,6160	20,9
SD AMD, 24h	1,3840	–
SD AMD + 5 ml inhibitor, 24h	1,3200	4,6

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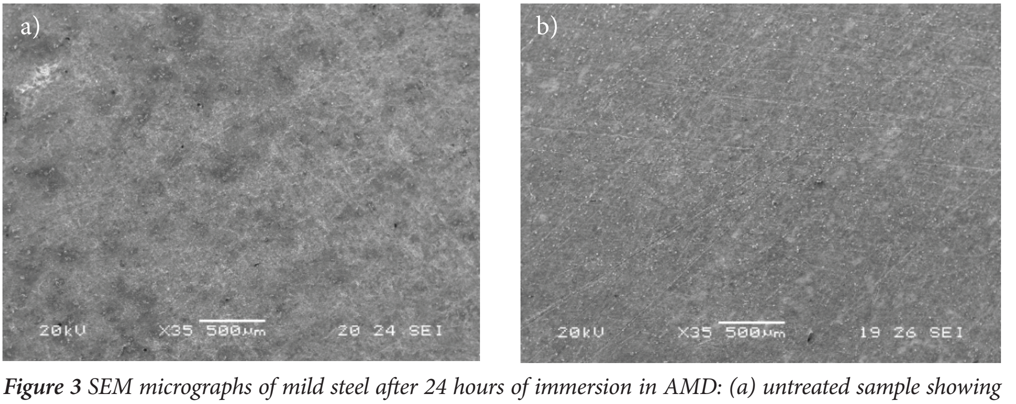

Figure 3 *SEM micrographs of mild steel after 24 hours of immersion in AMD: (a) untreated sample showing extensive corrosion; (b) sample treated with spent coffee extract.*

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