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Evaluation of cactus mucilage as a green corrosion inhibitor for copper in sulfuric acid environment

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Abstract. This study investigates the corrosion inhibition performance of cactus mucilage for copper in 0.5 M H_2SO_4 solution. The cactus mucilage was extracted using a pure water extraction method and characterized using FTIR and GC-MS analyses. The inhibition efficiency was evaluated using potentiodynamic polarization and EIS techniques, while surface morphology was analyzed using SEM and AFM. The potentiodynamic polarization results revealed that cactus mucilage acts as a mixed-type inhibitor, with inhibition efficiency increasing from 78.6% at 100 mg L^{-1} to 94.5% at 600 mg L^{-1}. The EIS measurements showed a significant increase in charge transfer resistance from 0.56 kΩ cm^{-2} in the uninhibited solution to 8.26 kΩ cm^{-2} with 600 mg L^{-1} cactus mucilage. The adsorption of cactus mucilage on the copper surface followed the Langmuir isotherm model, with a strong adsorption equilibrium constant of 23.6 × 103 M. Compared to other green inhibitors, cactus mucilage exhibited superior inhibition efficiency and sustainability advantages, making it a promising eco-friendly alternative for copper corrosion protection.

Key words: polysaccharides, adsorption, surface analysis, eco-friendly, sustainable.

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Introduction

Copper, a widely used metal in various industrial applications, is renowned for its excellent thermal and electrical conductivity, ductility, and malleability (Xu *et al*., 2023). However, copper is susceptible to corrosion when exposed to aggressive environments, particularly in acidic media such as sulfuric acid (Diki *et al*., 2021; Deyab *et al.,* 2024). The corrosion of copper leads to significant economic losses, reduced equipment lifespan, and potential safety hazards (Bastidas *et al*., 2010). Therefore, the development of effective corrosion inhibitors is crucial to mitigate the detrimental effects of corrosion on copper and extend the service life of copper-based equipment (Shinato *et al*., 2020; Kadhim *et al*., 2022; Eid *et al*., 2024). Traditionally, synthetic organic compounds containing heteroatoms such as nitrogen, sulfur, and oxygen have been employed as corrosion inhibitors for copper (Zhang *et al*., 2023). These compounds adsorb onto the metal surface, forming a protective barrier (Merdas *et al*., 2021). While these inhibitors have shown good performance, many of them are toxic, non-biodegradable, and pose environmental concerns (Lavanya *et al*., 2024). Moreover, the synthesis of these compounds often involves complex processes and high costs. The complexity arises from the need for precise control over reaction conditions, such as temperature, pressure, and pH, to ensure the correct molecular structure and functionality of the inhibitors

(Bharatiya *et al*., 2019). These processes may require multiple steps, including purification and isolation of intermediates, which further increase the overall cost. Additionally, the use of expensive reagents and catalysts adds to the financial burden (Prasad *et al*., 2020). As a result, there is a growing need for green, eco-friendly, and sustainable alternatives to traditional corrosion inhibitors.

In recent years, plant extracts have emerged as promising candidates for green corrosion inhibitors (Fouda *et al*., 2015; Tasić *et al*., 2019). These natural products are readily available, renewable, biodegradable, and non-toxic. Various plant species have been studied for their corrosion-inhibiting properties. For instance, extracts from the leaves of *Azadirachta indica* (neem), which is native to the Indian subcontinent, have shown significant effectiveness. Similarly, the seeds of *Moringa oleifera*, also indigenous to India and parts of Africa, are utilized for their inhibitory properties. In addition, the bark of *Quercus suber* (cork oak), found in the Mediterranean region, has been investigated for its potential as a corrosion inhibitor. These plant parts are rich in bioactive compounds such as tannins, alkaloids, and flavonoids, which contribute to their effectiveness in corrosion prevention (Krishnaveni and Ravichandran, 2015; Salem *et al*., 2023). The adsorption of these compounds is attributed to the presence of lone pairs of electrons on the heteroatoms, as well as the pi-electrons of the aromatic rings. Additionally, plant extracts are cost-effective compared to synthetic inhibitors, as they can be obtained through simple extraction processes. The extracts from leaves, fruits, seeds, and barks of plants such as *Carica papaya* (Nwigwe *et al*., 2019), *Luffa cylindrica* (Jyothi and Ravichandran, 2015), *Ginkgo biloba* (Chen *et al*., 2023), and *Magnolia grandiflora* (Li *et al*., 2023; Rivas-Garcia *et al.,* 2023) have shown excellent inhibition efficiency for copper corrosion in hydrochloric acid and sulfuric acid solutions. These studies have demonstrated the potential of plant extracts as green corrosion inhibitors, highlighting their adsorption behavior, inhibition mechanism, and the influence of factors such as temperature and inhibitor concentration.

Among the diverse plant species, cactus has gained attention as a potential source of green corrosion inhibitors. López-León *et al*. (2019) investigated the use of cactus mucilage as a corrosion-resistant coating for steel reinforcement in concrete structures. These researchers extracted mucilage from *Opuntia streptacantha* and formulated coatings with varying concentrations (0.2 to 0.5 g) to assess their protective performance against corrosion in a 3.5 wt% NaCl solution. The results demonstrated that the mucilage-based coatings significantly enhanced corrosion resistance, with the highest mucilage concentration (0.5 g) achieving the best performance. Torres-Acosta (2007) investigated the use of *Opuntia ficus-indica* (nopal) mucilage as a corrosion inhibitor for reinforcing steel in alkaline media. The research aimed to explore an environmentally friendly alternative to conventional toxic corrosion inhibitors. Dehydrated nopal was mixed with saturated calcium hydroxide solutions at concentrations of 0.5, 1.0, and 2.0% by weight. The results indicated that nopal significantly improved corrosion resistance, with polarization resistance values increasing from an average of 40 kΩ cm^{-2} in chloride-contaminated solutions without nopal to 150 kΩ cm^{-2} with nopal. This enhancement was attributed to the formation of a denser oxide/hydroxide layer on the steel surface, reducing corrosion activity. The cactus, a succulent plant adapted to arid and semi-arid regions, is known for its ability to store water in its thick, fleshy stems and leaves (Novoa *et al*., 2015). The mucilage present in cactus, a complex polysaccharide, has been explored for various applications, including food, cosmetics, and pharmaceuticals (Dubeux *et al*., 2021; Jardim *et al*., 2023). The cactus mucilage is composed of sugars, proteins, and minerals, which contain functional groups that can interact with metal surfaces (Andrade-Vieira *et al*., 2023). Moreover, cactus is abundant, easily cultivated, and requires minimal water and maintenance, making it an attractive and sustainable source of corrosion inhibitors. Despite the promising potential of cactus mucilage as a green corrosion inhibitor, limited research has been conducted on its application for copper corrosion inhibition in sulfuric acid environment. Therefore, the present study aims to evaluate the corrosion inhibition ability of cactus mucilage for copper in H_2SO_4. The main objectives of this study are, 1) To extract cactus mucilage using an eco-friendly and efficient pure water extraction method; 2) To characterize the extracted cactus mucilage using FTIR analysis

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and identify its main chemical components; and 3) To analyze the surface morphology of copper before and after corrosion tests using SEM and AFM.

Material and Methods

Extraction of cactus mucilage

The cactus stems from the species *Opuntia Milpa Alta* were collected from the Gobi Desert in Gansu Province, China. This species was selected due to its remarkable adaptability to arid environments, characterized by its thick, fleshy pads that store water efficiently. *Opuntia Milpa Alta* is known for its high nutritional and bioactive compound content, including vitamins and antioxidants, which are beneficial for various applications. The pads were chosen for their size, maturity, and health to ensure they were free from diseases and pests. These characteristics make them ideal for studies focused on nutritional analysis and bioactive compound extraction. The collected stems were thoroughly washed with water, cut into small pieces, and dried in an oven at 60 °C for 48 hours. The dried cactus pieces were then ground into a fine powder using a high-speed pulverizer.

The cactus mucilage was extracted using a pure water extraction method (Mannai *et al*., 2023). A total of 100 g of cactus powder was mixed with 1 L of water in a 2 L glass beaker. The mixture was sonicated and the filtrate was concentrated using a rotary evaporator at 60 °C under reduced pressure. The concentrated mucilage was then freeze-dried using a lyophilizer to obtain a fine powder. The dried cactus mucilage powder was stored in an airtight container for further use.

Corrosion inhibition evaluation methods

The evaluation was adopted from Stupnišek-Lisac *et al*. (2002) with some modifications. Copper specimens with a composition of 99.9 wt% Cu were used for the corrosion tests. The specimens were cut into rectangular pieces with dimensions of 10 mm × 10 mm × 2 mm. Prior to the experiments, the specimens were mechanically ground with a series of emery papers (grades: 400, 800, 1200, and 2000) to obtain a smooth surface. The polished specimens were then washed with distilled water, degreased with acetone, and dried in a stream of warm air.

The corrosive medium used in this study was a 0.5 M sulfuric acid (H_2SO_4) solution. The solution was prepared by diluting concentrated H_2SO_4 (with ultrapure water). The cactus mucilage was added to the H_2SO_4 solution at concentrations of 100, 200, 400, and 600 mg L^{-1} to prepare the inhibited solutions.

The potentiodynamic polarization measurements were carried out using a CHI660E electrochemical workstation (YIMA®). The polarization curves were recorded in the potential range of ± 250 mV versus the open circuit potential (OCP) at a scan rate of 1 mV/s. The corrosion current density (icorr), corrosion potential (Ecorr), anodic Tafel slope (βa), and cathodic Tafel slope (βc) were obtained from the polarization curves using the Tafel extrapolation method.

EIS measurements were performed using the same electrochemical workstation and three-electrode cell setup as described for the polarization measurements. The EIS spectra were recorded at the OCP in the frequency range of 100 kHz to 10 mHz with an AC perturbation amplitude of 5 mV.

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Characterization

Fourier Transform Infrared (FTIR) spectroscopy was utilized to analyze the chemical composition of cactus mucilage. The mucilage was first freeze-dried to obtain a powdered sample, which was then placed on an Attenuated Total Reflectance accessory of an FTIR spectrometer. The spectra were recorded over a range of 4,000 cm^{-1} to 400 cm^{-1}, with each spectrum being the average of 32 scans at a resolution of 4 cm^{-1}, ensuring a high signal-to-noise ratio. The background spectrum was subtracted to account for atmospheric interference.

The cactus mucilage was prepared by first extracting it from the dried and powdered cactus pads using a pure water extraction method. After extraction, the mucilage was subjected to GC-MS analysis to determine its chemical profile. The GC-MS analysis was conducted using an Agilent Technologies® 7890A gas chromatograph coupled with a 5975C mass selective detector. The system was equipped with a DB-5MS capillary column (30 m × 0.25 mm i.d., 0.25 μm film thickness). The injection volume was set at 1 μL, with a split ratio of 10:1. Helium was used as the carrier gas at a constant flow rate of 1 mL min-1.

The surface morphology of the copper specimens before and after the corrosion tests was observed using a TESCAN® MIRA3 SEM. The specimens were immersed in the uninhibited and inhibited 0.5 M H_2SO_4 solutions for 6 h at 25 °C. After the immersion period, the specimens were removed, rinsed with water, and dried in a desiccator. The surface topography and roughness of the copper specimens were analyzed using a Bruker® MultiMode 8 AFM. The specimens were prepared in the same manner as described for the SEM analysis. The AFM images were acquired using a silicon nitride cantilever with a nominal tip radius of 10 nm and a resonance frequency of 300 kHz.

Results and Discussion

FTIR results and chemical composition of cactus mucilage

Figure 1 shows the FTIR spectrum of the extracted cactus mucilage. The peak observed at 3424 cm^{-1} is attributed to the stretching vibrations of the hydroxyl (O-H) groups, indicating the presence of polysaccharides and sugars in the mucilage. The peaks at 2935 cm^{-1} correspond to the asymmetric and symmetric stretching vibrations of the C-H bonds (Rivera-Corona *et al*., 2014), respectively. The peak at 1687 cm^{-1} belongs to the carbonyl groups, suggesting the presence of uronic acids or proteins in the mucilage (Otálora *et al*., 2019). The peak at 1420 cm^{-1} is attributed to the bending vibrations of the C-H bonds in the methylene groups (Fox *et al*., 2012). The absorption bands in the region of 1200-1000 cm^{-1} are characteristic of the C-O-C and C-O-H stretching vibrations of the glycosidic bonds and hydroxyl groups in the polysaccharide structure (Camelo-Caballero *et al*., 2019). The analysis of the FTIR spectrum is crucial in understanding the chemical interactions and composition of cactus mucilage, which plays a significant role in its effectiveness as a corrosion inhibitor for copper in sulfuric acid. FTIR spectroscopy provides detailed information about the functional groups present in the mucilage, such as hydroxyl, carbonyl, and glycosidic bonds. These groups are essential for adsorption onto the copper surface, forming a protective barrier that reduces corrosion. By identifying the specific chemical components through FTIR, it is possible to infer the potential mechanisms by which the mucilage inhibits corrosion. For instance, the presence of polysaccharides and sugars, as indicated by the FTIR peaks, suggests that these components facilitate the formation of a cohesive film on the metal surface. This film acts as a physical barrier, preventing corrosive agents from reaching the copper. Additionally, the FTIR analysis supports the characterization of the mucilage's molecular structure, which is vital for optimizing its extraction and application processes.

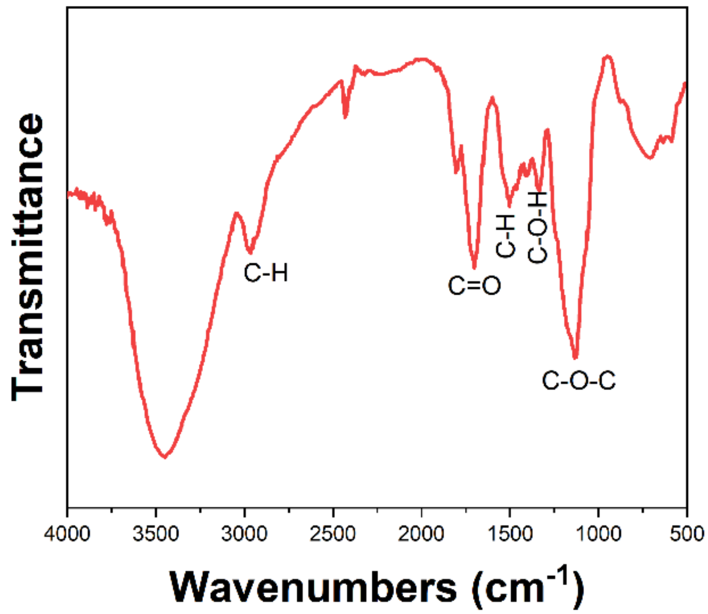

Figure 1. FTIR spectrum of the extracted cactus mucilage.

The GC-MS test of cactus mucilage showed the presence of a series of chemical components (Table 1). The major constituents identified in the mucilage were D-glucose (28.6%), D-galactose (19.2%), D-xylose (12.5%), L-rhamnose (10.8%), and D-glucuronic acid (8.4%). These results suggest that the cactus mucilage is primarily composed of polysaccharides, with minor amounts of uronic acids and other monosaccharides. The presence of these functional groups and chemical components in the cactus mucilage contributes to its potential as a corrosion inhibitor for copper in sulfuric acid solution. These naturally occurring polymers contain multiple hydroxyl groups, which facilitate strong adsorption onto the copper surface (Chen *et al*., 2003). This adsorption is primarily due to the formation of hydrogen bonds and van der Waals interactions between the polysaccharide molecules and the metal surface. Once adsorbed, the polysaccharides form a protective layer that acts as a physical barrier, preventing the aggressive sulfuric acid solution from directly interacting with the copper surface (AL Salihi *et al*., 2024). This barrier reduces the rate of corrosion by limiting the metal's exposure to corrosive ions. Furthermore, the polysaccharides' large molecular structure enhances the cohesiveness and stability of this protective film, ensuring effective and sustained inhibition over time. Additionally, the presence of other functional groups, such as carboxyl and ester groups, may contribute to the chelation of metal ions, further enhancing the protective film's stability (Mobin *et al*., 2017). This multifaceted interaction between polysaccharides and the copper surface underscores their effectiveness as corrosion inhibitors, highlighting the eco-friendly and sustainable potential of cactus mucilage in industrial applications.

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Table 1. Chemical composition of the cactus mucilage determined by GC-MS analysis.

Component	**Percentage (%)**
D-glucose	28.6 ± 1.2
D-galactose	19.2 ± 0.8
D-xylose	12.5 ± 0.6
L-rhamnose	10.8 ± 0.5
D-glucuronic acid	8.4 ± 0.4
D-mannose	6.7 ± 0.3
L-arabinose	5.2 ± 0.2
D-fructose	3.8 ± 0.2
D-ribose	2.6 ± 0.1
Others	2.2 ± 0.1

Potentiodynamic polarization results

The potentiodynamic polarization curves for copper in 0.5 M H_2SO_4 solution without and with different concentrations of cactus mucilage are shown in figure 2. In the absence of the inhibitor, the polarization curve exhibits high anodic and cathodic current densities, indicating the active dissolution of copper in the acidic medium. As the concentration of cactus mucilage increases from 100 to 600 mg L^{-1}, a significant decrease in both the anodic and cathodic current densities is observed (Alateyah *et al*., 2021). This response suggests that the cactus mucilage acts as a mixed-type inhibitor (Peng *et al*., 2021). A mixed-type inhibitor is a substance that can simultaneously reduce both anodic and cathodic reactions occurring on a metal surface during corrosion. In the context of this study, cactus mucilage acts as a mixed-type inhibitor for copper in sulfuric acid. It achieves this by forming a protective film on the copper surface, which impedes the metal's dissolution (anodic reaction) and the reduction of hydrogen ions (cathodic reaction). This dual functionality is evident from the potentiodynamic polarization curves, where both anodic and cathodic current densities decrease significantly with increasing concentrations of cactus mucilage, confirming its mixed-type inhibition behavior. The shift in the corrosion potential towards positive with increasing inhibitor concentration further confirms the predominant anodic inhibition effect of the cactus mucilage.

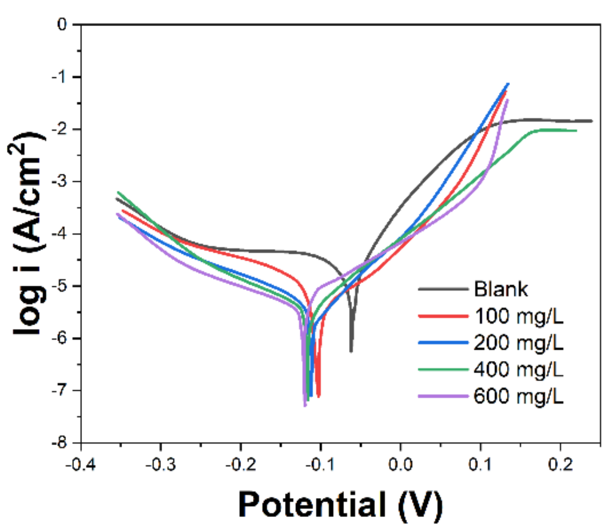

Figure 2. Potentiodynamic polarization curves for copper in 0.5 M H_2SO_4 solution without and with different concentrations of cactus mucilage.

The corrosion parameters, including the icorr, Ecorr, βa, βc, and η%, obtained from the polarization curves are summarized in table 2. The icorr values decrease with increasing concentrations of cactus mucilage, indicating the reduction in the corrosion rate of copper in the presence of the inhibitor. The inhibition efficiency (η%) increases from 78.6% at 100 mg L^{-1} to 94.5% at 600 mg L^{-1}, demonstrating the excellent corrosion inhibition performance of the cactus mucilage. The increase in inhibition efficiency is attributed to the enhanced adsorption of cactus mucilage molecules on the copper surface. This adsorption forms a more cohesive and dense protective film, which effectively blocks the active sites on the metal surface, reducing both anodic and cathodic reactions. The polysaccharides and functional groups present in the mucilage, such as hydroxyl and carbonyl groups, facilitate strong interactions with the copper surface, leading to a more stable and efficient barrier against corrosion. This results in improved corrosion resistance as the concentration of mucilage increases. The anodic and cathodic Tafel slopes do not show a significant change in the presence of the inhibitor, suggesting that the cactus mucilage does not alter the corrosion mechanism of copper in sulfuric acid solution.

Table 2. Corrosion parameters and inhibition efficiency obtained from potentiodynamic polarization measurements for copper in 0.5 M H_2SO_4 solution without and with different concentrations of cactus mucilage.

Concentration of cactus mucilage (mg L^{-1})	**Ecorr (mV vs. SCE)**	**icorr (μA cm^{-2})**	**βa (mV dec^{-1})**	**βc (mV dec^{-1})**	**η (%)**
0 (Blank)	-48	18.6	76	-128	-
100	-32	3.9	69	-119	78.6
200	-27	2.7	65	-114	85.2
400	-21	1.5	62	-110	91.8
600	-18	1.0	60	-107	94.5

The adsorption response of the cactus mucilage on the copper surface was investigated by fitting the surface coverage data (θ) obtained from the polarization measurements to various adsorption isotherm models (Dong *et al*., 2022). The Langmuir adsorption isotherm was found to provide the best fit, as shown in Figure 3. The R^2 of 0.998 confirms the applicability of the Langmuir isotherm to describe the adsorption of cactus mucilage on the copper surface. The Langmuir isotherm assumes monolayer adsorption and homogeneous binding sites on the metal surface (Ge and Isgor, 2007). The slope of the Langmuir plot is close to unity, indicating the inhibitor film formed on the copper surface. The calculated adsorption equilibrium constant (Kads) was found to be 23.6 × 10^3 M, suggesting strong adsorption of the cactus mucilage molecules on the copper surface.

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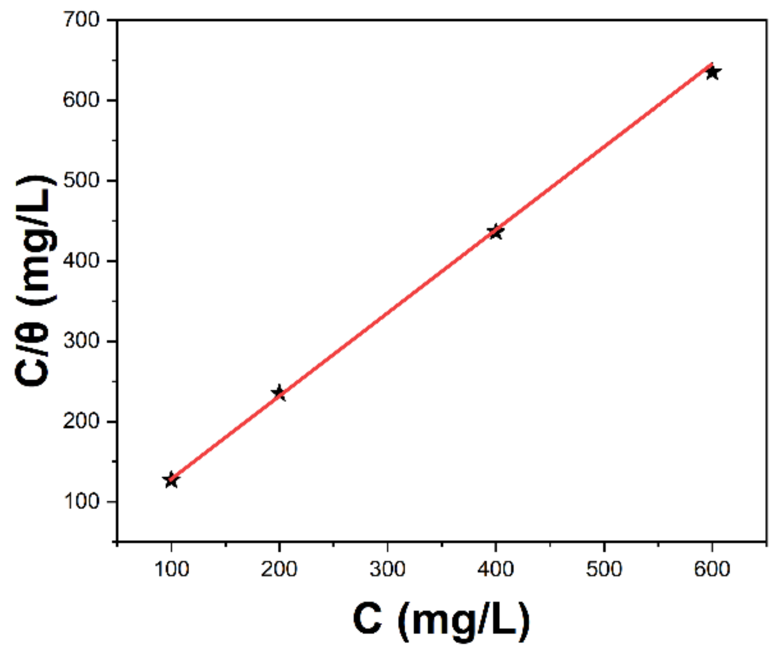

Figure 3. Langmuir adsorption isotherm plot for the adsorption of cactus mucilage on the copper surface.

EIS results

The Nyquist and Bode plots for copper in 0.5 M H_2SO_4 solution without and with different concentrations of cactus mucilage are shown in Figure 4 and Figure 5, respectively. The Nyquist plot (figure 4) shows a larger diameter of the semicircle with more cactus mucilage, suggesting an advanced corrosion resistance of copper in the presence of the inhibitor (Jarjoura and Kipouros, 2006). The largest semicircle is observed for the highest concentration of cactus mucilage (600 mg L^{-1}), suggesting the formation of a protective film on the copper surface that effectively hinders the corrosion process (El-Feky *et al*., 2010).

The Bode plots (figure 5) provide further insights into the corrosion inhibition mechanism of the cactus mucilage. In the absence of the inhibitor, the impedance modulus (|Z|) at low frequencies is relatively low, indicating the active dissolution of copper in the acidic medium (Porcayo-Calderon *et al*., 2015). With the addition of cactus mucilage, the impedance modulus values increase significantly, especially at lower frequencies. This reaction suggests the formation of a stable and resistant inhibitor film on the copper surface that impedes the corrosion reaction (Parida *et al*., 2024). The phase angle plot (figure 5b) shows a single peak in the absence of the inhibitor, which is characteristic of a capacitive response. In the presence of cactus mucilage, the phase angle peak broadens and shifts towards higher frequencies, indicating the enhancement of the capacitive behavior and the reduction of the corrosion rate (Sayed *et al*., 2003).

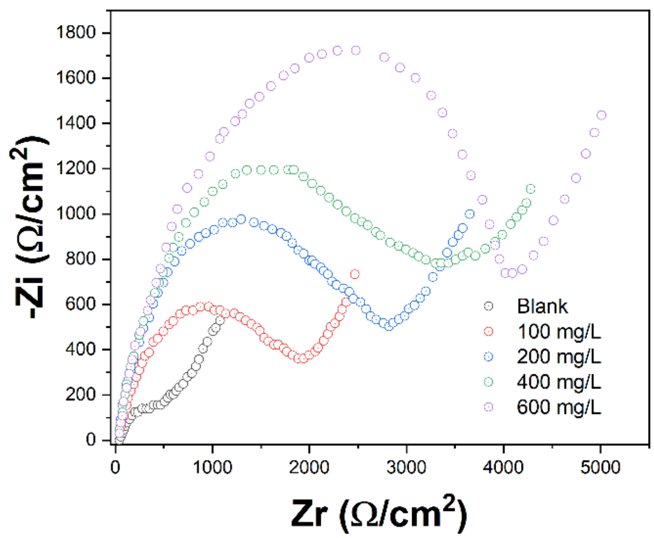

Figure 4. Nyquist plots for copper in 0.5 M H_2SO_4 solution without and with different concentrations of cactus mucilage.

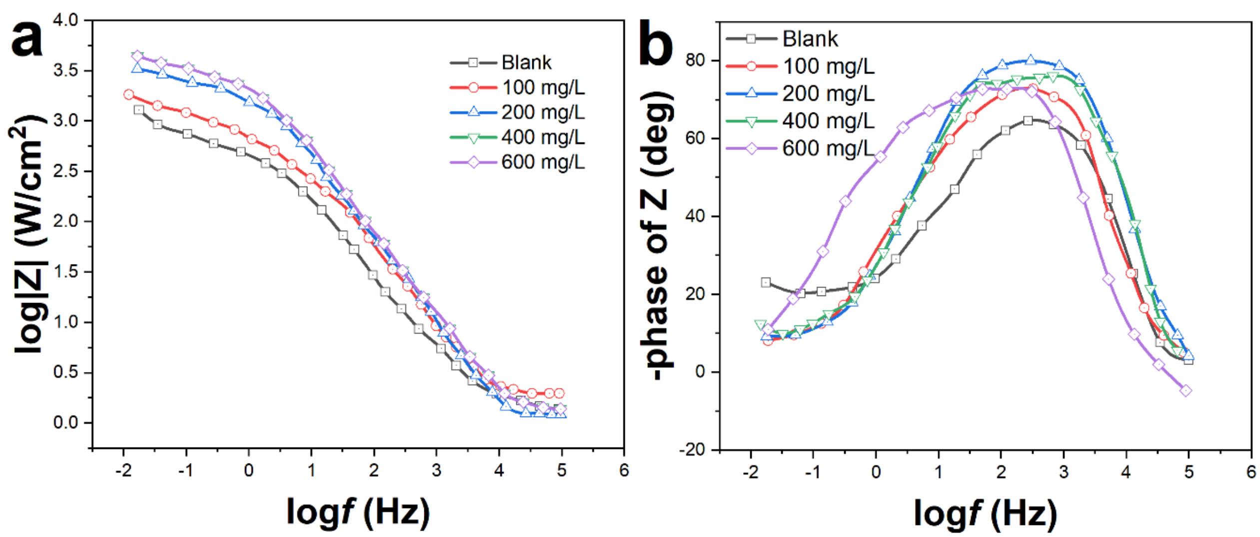

Figure 5. Bode plots for copper in 0.5 M H_2SO_4 solution without and with different concentrations of cactus mucilage: (a) impedance modulus vs. frequency, and (b) phase angle vs. frequency.

The EIS data were analyzed by fitting to an equivalent circuit model. The equivalent circuit consists of the Rs, the Rct, and a CPE representing the double-layer capacitance. The CPE is used instead of an ideal capacitor to account for the non-homogeneity and roughness of the electrode surface. The impedance parameters obtained from the equivalent circuit fitting are listed in table 3. The charge transfer resistance (Rct) increases significantly with increasing concentrations of cactus mucilage, confirming the enhanced corrosion inhibition efficiency of the inhibitor. The highest Rct value of 8.26 kΩ cm^{-2} is obtained for 600 mg L^{-1} of cactus mucilage, which is approximately 15 times higher than that of the uninhibited solution. The CPE exponent (n) values are close to unity, indicating the capacitive behavior of the double layer. The decrease in the CPE constant (Q) with increasing inhibitor concentration suggests the formation of a protective film on the copper surface that reduces the exposed surface area (Zhang *et al*., 2003; Zhang and Hua, 2011).

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Table 3. Impedance parameters obtained from the equivalent circuit fitting copper in 0.5 M H_2SO_4 solution without and with different concentrations of cactus mucilage.

Concentration (mg L^{-1})	Rs (Ω cm-2)	Rct (kΩ cm^{-2})	Q (μF cm^{-2})	n
0 (Blank)	1.2	0.56	98	0.88
100	1.3	2.64	61	0.91
200	1.4	3.87	47	0.92
400	1.5	5.92	36	0.93
600	1.6	8.26	28	0.94

Surface morphology analysis

The surface morphology of the copper specimens before and after immersion in 0.5 M H_2SO_4 solution without and with 600 mg L^{-1} of cactus mucilage was examined using SEM (Figure 6). The polished copper (Figure 6a) has a smooth morphology, with some minor polishing lines. The H_2SO_4 immersion for 6 h (Figure 6b) leads to corroded surface morphology, with deep pits and rough, uneven morphology. The aggressive corrosion of copper observed after immersion in 0.5 M H_2SO_4 for 6 h, resulting in a rough and pitted surface morphology, is attributed to the acidic environment's ability to facilitate the rapid dissolution of copper ions. In such an acidic medium, the hydrogen ions are highly reactive, promoting the breakdown of the copper surface and resulting in the formation of pits and an uneven texture. This process is exacerbated by the absence of any protective barrier, allowing the sulfuric acid to penetrate and corrode the metal more effectively. The lack of inhibitor in the solution means that there is no interference with the electrochemical reactions occurring on the copper surface, leading to accelerated corrosion. The SEM images clearly demonstrate the impact of the acid, highlighting the necessity for an effective corrosion inhibitor, such as cactus mucilage, to prevent such degradation and maintain the integrity of the copper surface.

The copper immersed in the H_2SO_4 containing 600 mg L^{-1} of cactus mucilage (Figure 6c) exhibits a significantly improved morphology. The surface appears much smoother and less corroded compared to the uninhibited specimen. The presence of a thin, protective film can be observed on the surface, which effectively suppresses the corrosion of copper.

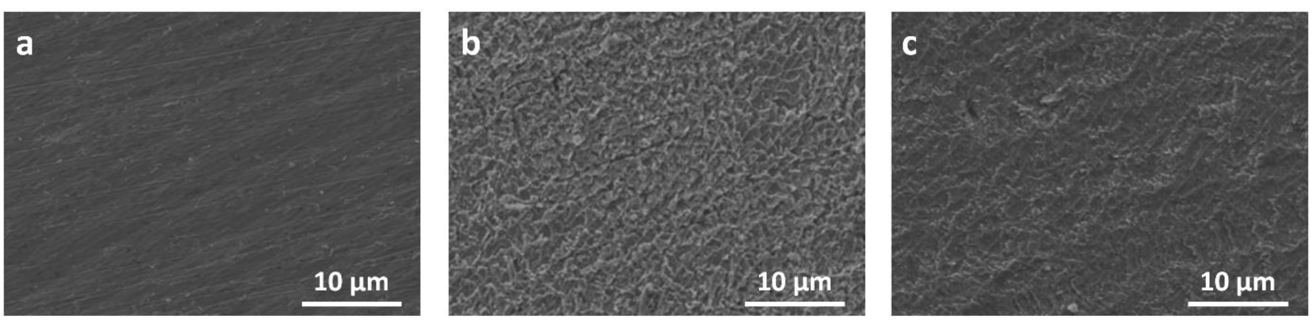

Figure 6. SEM images of copper surfaces: (a) after polishing, (b) with 6 h 0.5 M H_2SO_4, and (c) with 6 h 0.5 M H_2SO_4 containing 600 mg L^{-1} of cactus mucilage.

The surface topography and roughness of the copper specimens were further investigated using AFM. The three-dimensional AFM images and corresponding roughness profiles of the copper surfaces before and after immersion in 0.5 M H_2SO_4 solution without and with 600 mg L^{-1} of cactus mucilage are shown in figure 7. The polished copper before immersion (Figure 7a) shows a relatively smooth topography with an average roughness (Ra) of 12.6 nm and a root-mean-square roughness (Rq) of 15.8 *nm*.

After immersion in the uninhibited H_2SO_4 solution (Figure 7b), the copper surface becomes highly corroded and rough, with an increased Ra value of 186.4 nm and an Rq value of 235.7 *nm*. The surface exhibits deep cavities and a non-uniform morphology, indicating severe corrosion damage. In the presence of 600 mg L^{-1} of cactus mucilage (Figure 7c), the surface roughness is significantly reduced, with Ra and Rq values of 28.2 *nm* and 35.6 *nm*, respectively. The surface appears much smoother and more homogeneous compared to the uninhibited specimen, confirming the formed protective layer by the cactus mucilage that mitigates the corrosion of copper.

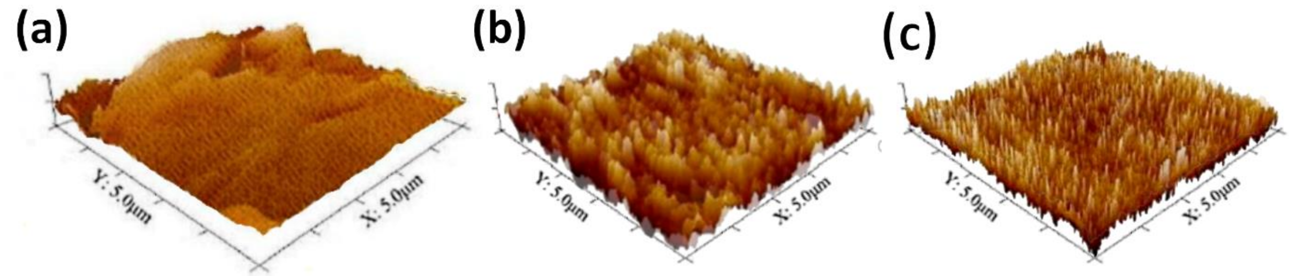

Figure 7. Three-dimensional AFM images and rough profiles of copper surfaces: (a) after polishing, (b) with 6 h 0.5 M H_2SO_4, and (c) with 6 h 0.5 M H_2SO_4 containing 600 mg L^{-1} of cactus mucilage.

The corrosion inhibition efficiency of cactus mucilage for copper in 0.5 M H_2SO_4 solution was compared with other bio-based extract inhibitors, as shown in table 4. The cactus mucilage exhibits a higher inhibition efficiency (94.5% at 600 mg L^{-1}) compared to *Luffa cylindrica* leaf extract (94.0% at 2000 mg L^{-1}), Ginkgo leaf extract (93.6% at 1000 mg L^{-1}), and *Carica papaya* leaf extract (92.5% at 150 mg L^{-1}). The superior performance of cactus mucilage can be attributed to its unique composition of polysaccharides and functional groups that facilitate strong adsorption on the copper surface.

Moreover, cactus mucilage is readily available, biodegradable, and non-toxic, making it an attractive and sustainable alternative to synthetic corrosion inhibitors. The extraction process of cactus mucilage is simple and eco-friendly, involving only water as the solvent. These advantages, coupled with its excellent corrosion inhibition efficiency, highlight the potential of cactus mucilage as a green corrosion inhibitor for copper in acidic environments.

To enhance the discussion on the mechanisms underlying the inhibitory effect of cactus mucilage on copper corrosion, it is crucial to delve deeper into the interaction between the inhibitor and the metal surface. The inhibitory action of cactus mucilage is primarily attributed to the adsorption of its bioactive compounds onto the copper surface, forming a protective barrier that reduces the metal's exposure to the corrosive environment. This adsorption process can be explained by the Langmuir isotherm model, which suggests a monolayer adsorption mechanism where the active sites on the metal surface are occupied by the inhibitor molecules.

The effectiveness of this adsorption is evidenced by the significant increase in Rct observed in the EIS measurements, which indicates a reduction in the rate of electron transfer processes that drive corrosion. Additionally, the potentiodynamic polarization studies reveal that while the anodic and

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cathodic Tafel slopes remain largely unchanged, the icorr decreases substantially with increasing concentrations of cactus mucilage. This suggests that the inhibitor does not alter the fundamental electrochemical reactions but effectively slows down their rates by blocking the active sites on the copper surface.

Furthermore, the presence of polysaccharides and other organic compounds in cactus mucilage likely contributes to its high inhibition efficiency. These compounds contain functional groups such as hydroxyl and carboxyl groups, which have a strong affinity for metal surfaces, enhancing the adsorption process. The protective film formed is robust enough to withstand the acidic environment, thereby providing sustained protection against corrosion.

Table 4. Comparison of the inhibition efficiency of cactus mucilage with other reported green corrosion inhibitors for copper in 0.5 M H_2SO_4 solution.

Inhibitor	Concentration (mg L^{-1})	Inhibition Efficiency (%)	Reference
Cactus mucilage	600	94.5	This work
***Pistacia lentiscus* extract**	2000	94.0	(Dahmani *et al*., 2022)
***Rosa laevigata* extract**	300	89.8	(Zhang *et al*., 2022)
Bee pollen extract	4000	94.5	(Ahmed and Zhang, 2020)
***Leonurus japonicus* Houtt. extract**	400	90.0	(Xu *et al*., 2022)
***Atriplex leucoclada* extract**	5000	91.5	(Ahmed and Zhang, 2021)

Conclusions

This study demonstrates the excellent potential of cactus mucilage as a green and eco-friendly corrosion inhibitor for copper in 0.5 M H_2SO_4 solution. The cactus mucilage, extracted using a simple and sustainable pure water extraction method, contains polysaccharides and functional groups that facilitate strong adsorption on the copper surface. FTIR analysis confirmed the presence of hydroxyl, carbonyl, and glycosidic bonds in the mucilage, while GC-MS revealed the main chemical components, including D-glucose (28.6%), D-galactose (19.2%), and D-xylose (12.5%). Potentiodynamic polarization measurements showed that cactus mucilage acts as a mixed-type inhibitor, with an inhibition efficiency increasing from 78.6% at 100 mg L^{-1} to 94.5% at 600 mg L^{-1}. EIS results further confirmed enhanced corrosion resistance, with the charge transfer resistance increasing from 0.56 kΩ cm^{-2} in the uninhibited solution to 8.26 kΩ cm^{-2} in the presence of 600 mg L^{-1} cactus mucilage. SEM and AFM analyses provided visual evidence of the protective film formed by the cactus mucilage, significantly reducing surface roughness and corrosion damage. Compared to other green corrosion inhibitors, cactus mucilage exhibits superior inhibition efficiency and sustainability advantages, highlighting its promise as a green alternative to synthetic corrosion inhibitors for copper in acidic environments.

ETHICS STATEMENT

Not applicable

CONSENT FOR PUBLICATION

Not applicable

COMPETING INTEREST

The authors declare that they have no competing interests.

AVAILABILITY OF SUPPORTING DATA

Not applicable

AUTHOR CONTRIBUTION

Conceptualization, X.Z. and L.H.; methodology, L.H.; software, L.H.; validation, X.Z. and L.H.; formal analysis, X.Z.; investigation, X.Z.; resources, L.H.; data curation, L.H.; writing—original draft preparation, X.Z.; writing—review and editing, L.H.; visualization, X.Z; supervision, L.H.; project administration, L.H.

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