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Unveiling the Corrosion Inhibition Potential of *Orbea variegata* Extract: A Sustainable, Bio-Based Novel Inhibitor for Mild Steel in HCl

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ABSTRACT

This study explores the corrosion inhibition performance of an aqueous extract derived from *Orbea variegata*, a succulent plant commonly known as "Carrion cactus" used as a green, bio-based inhibitor for mild steel electrode in 1.0 M hydrochloric acid. The corrosion behaviour was evaluated using potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) following a 1-hour immersion period in acidic medium. Four different extract concentrations (0.005%, 0.010%, 0.050%, and 0.200% *w/v*) were tested to assess dose-dependent inhibition efficiency. Surface morphological changes of the mild steel samples were also surveyed via field-emission scanning electron microscopy (FE-SEM). Electrochemical results revealed a marked improvement in corrosion resistance with increasing extract concentration, demonstrating that *Orbea variegata* extract effectively suppresses corrosion processes owing to adsorption on the metallic surface. At all tested concentrations, the inhibition efficiency exceeded 90%, highlighting the potential of this plant as a sustainable alternative to conventional inhibitors. The findings suggest that *Orbea variegata* extract could serve as an eco-friendly, efficient and sustainable corrosion inhibitor for industrial applications where acidic environments are prevalent.

Orbea variegata Ekstraktının Korozyon İnhibisyon Potansiyelinin Ortaya Konulması: HCl Çözeltisindeki Yumuşak Çelik İçin Sürdürülebilir ve Biyo-Kaynaklı Yeni Bir Yeşil İnhibitör

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ÖZ

Bu çalışma, halk arasında "leş kaktüsü" olarak bilinen bir sukulent türü olan *Orbea variegata* bitkisinden elde edilen sulu ekstraktın, 1,0 M hidroklorik asit ortamında yumuşak çelik üzerindeki yeşil, biyo-kaynaklı korozyon inhibitörü olarak etkinliğini araştırmaktadır. Korozyon davranışı, asidik ortamda 1 saatlik daldırma sonrası potansiyodinamik polarizasyon ve elektrokimyasal impedans spektroskopisi (EIS) kullanılarak değerlendirilmiştir. Derişimlere bağlı inhibisyon etkinliğini belirlemek amacıyla dört farklı ekstrakt derişimi (% 0,005; % 0,010; % 0,050 ve % 0,200 *w/v*) incelenmiştir. Ayrıca, yumuşak çelik örneklerinin yüzey morfolojisindeki değişiklikler alan emisyon taramalı elektron mikroskobu (FE-SEM) ile değerlendirilmiştir. Elektrokimyasal sonuçlar, artan ekstrakt derişimi ile birlikte korozyon direncinde belirgin bir iyileşme olduğunu ortaya koymuş ve *Orbea variegata* ekstraktının metal yüzeyine adsorplanarak korozyon süreçlerini etkili bir şekilde baskıladığını göstermiştir. Tüm çalışılan derişimlerde inhibisyon etkinliği % 90'ın üzerinde bulunmuş olup, bu bitkinin geleneksel bilinen inhibitörlere sürdürülebilir bir alternatif olarak değerlendirilebileceğini ortaya koymuştur. Bulgular, *Orbea variegata* ekstraktının asidik ortamların yaygın olduğu endüstriyel uygulamalarda çevre dostu, etkili ve sürdürülebilir bir korozyon inhibitörü olarak kullanılabileceğini göstermektedir.

1. Introduction

Metals are indispensable materials in modern industries due to their remarkable mechanical strength, durability, and relatively low production cost. Among them, mild steel stands out as one of the most widely employed materials, on account of its favourable balance between mechanical properties and economic efficiency. It is extensively utilized in construction, automotive components, chemical processing equipment, pipelines, and various other structural applications (Hari Kumar et al., 2021). Despite its versatility, mild steel exhibits considerable vulnerability to corrosive attack, especially when exposed to acidic environments in various industrial operations involving acidic media, including metal surface activation, scale removal, and stimulation of oil-bearing formations (Raja and Sethuraman, 2008).

Acidic media, particularly hydrochloric acid, are frequently employed in industries to remove oxide layers or impurities from metal surfaces. However, these acid treatments inadvertently accelerate corrosion, resulting in material degradation, structural failure, elevated maintenance costs, and safety concerns. Corrosion in such environments is not only inevitable but also highly aggressive, often leading to severe economic and environmental consequences (Mahalakshmi et al., 2019). To mitigate these challenges, the utilization of corrosion inhibitors has become a crucial strategy. Corrosion inhibitors are chemically molecular compounds that, when added in little concentrations to a corrosive solution, significantly reduce the corrosion rate of metals by forming protective barriers at the interface of metal-solution (Gostin et al., 2012; Singh et al., 2012). Traditionally, many effective inhibitors have been inorganic compounds or synthetic organic compounds embodying hetero-atoms such as phosphorus, oxygen, sulphur, or nitrogen. While efficient, the long-term application of these inhibitors has raised serious environmental and toxicological concerns due to their persistence and potential bioaccumulation (Li et al., 2012).

In response to growing environmental awareness and sustainability goals, the focus has increasingly shifted to the progress of environmentally friendly and sustainable corrosion bio-inhibitors arise from natural sources, particularly plant extracts. These eco-friendly alternatives are biodegradable, renewable, and non-toxic, offering significant advantages over conventional inhibitors (Prabakaran et al., 2017; Haldhar et al., 2018; Casanova et al., 2023; Korniy et al., 2023). Plant extracts are rich in phytochemical constituents, including alkaloids, flavonoids, tannins, saponins, and other secondary metabolites. These compounds typically possess functional groups such as aromatic rings with π-electron systems, hydroxyl (-OH), and carbonyl (C=O), which facilitate their adsorption on the surfaces of metal (Hossain et al., 2022; Zakeri et al., 2022; Pahuja et al., 2023).

As highlighted in recent studies, increasing attention has been devoted to the development of eco-friendly corrosion inhibitors, particularly those derived from botanical sources. This growing interest is largely driven by environmental regulations and the urgent need for sustainable solutions. Numerous

plant-based substances, such as essential oils, alkaloid-rich extracts, and polyphenolic compounds, have shown remarkable effectiveness in protecting mild steel from aggressive acidic environments (Dehghani et al., 2019; Zouarhi et al., 2019). These natural inhibitors not only act through efficient surface adsorption but also offer significant advantages in terms of biodegradability and low toxicity, compared to their synthetic counterparts (Djenane et al., 2019; Hsissou et al., 2020). Several recent investigations further confirm the inhibitory potential of plant-derived compounds in HCl media, emphasizing their growing role in industrial corrosion management (Mungwari et al., 2025). Thus, integrating green inhibitors into corrosion protection strategies has become a central focus in advancing sustainable materials science.

The inhibition of corrosion mechanism by plant extracts is primarily ascribed to the constitution of an adsorbed presentative inhibitor film onto the surface. This layer acts as a barrier that limits the interaction between the corrosive species in the electrolyte and the metal. Adsorption can occur through physical forces (physisorption), chemical bonding (chemisorption), or a combination of both, relying on the nature of the extract components and the metallic surface (Obot et al., 2015; Solmaz et al., 2023). The effectiveness of inhibition generally increases with the concentration of active constituents in the extract, as more molecules become available to occupy and passivate active corrosion sites (Akalezi et al., 2020). The current study investigates the potential of *Orbea variegata*, a succulent species commonly referred to as "carrion cactus" and a novel, sustainable corrosion bio-inhibitor for mild steel in aggressive HCl solution. The aqueous extract of this plant, known for its unique morphology and metabolic profile, was conducted at four concentrations to evaluate its inhibition efficiency. The present study aims to contribute to the expanding field of bio-inhibition by providing evidence for the effectiveness of *O. variegata* extract, thereby supporting greener industrial practices and promoting the use of renewable natural resources in corrosion protection.

2. Materials and Methods

2.1. Plant material

Fresh aerial parts of *Orbea variegata*, a succulent plant widely known as "carrion flower or cactus" were collected from a cultivated pot in Niğde, Türkiye, during May 2025 (Figure 1). Fig. 1 displays different morphological views of the succulent, including stem texture and flower structure observed during the blooming stage. The plant was cultivated under controlled indoor conditions and utilized for aqueous extract preparation. The plant material was cleaned with distilled water to eliminate surface impurities. Afterwards, it was cut into small pieces with the help of scissors to obtain the aqueous extract.



Figure 1. *Orbea variegata* plant images used in this study

2.2. Preparation of Orbea variegata extract

Approximately 20 g of specimen were placed into a 500 mL round-bottom flask including 300 mL of distilled water. The mixture was subjected to gentle reflux heating for 16 hours. After cooling, the aqueous extract was filtered through filter (Whatman) paper to eliminate plant residues. The resulting solution, which had a dark brownish hue, was considered the stock extract (Fig. 2).

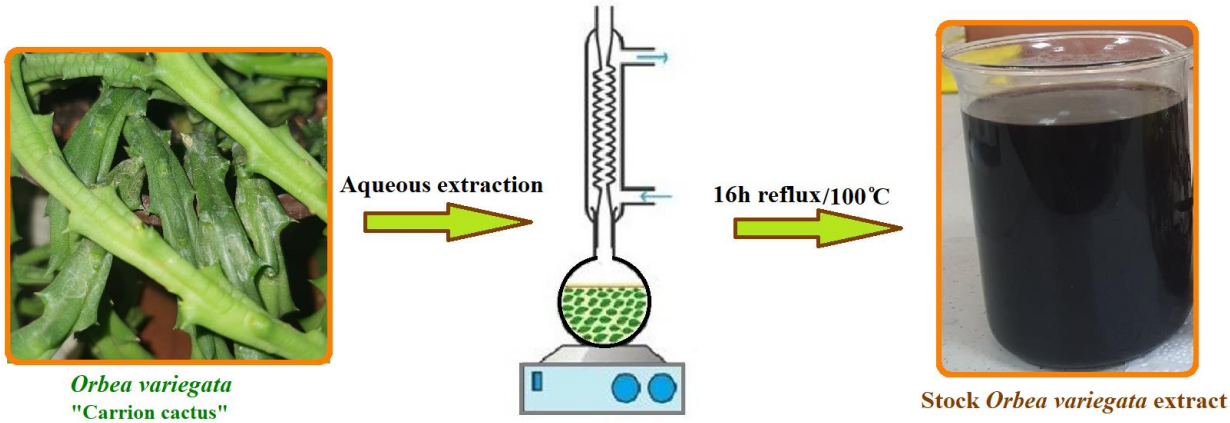


Figure 2. Schematic of *Orbea variegata* extraction procedure

The actual concentration of the stock solution was determined to be 1.974% (*w/v*) after 10 mL of the *Orbea variegata* extract was evaporated. This extract was further diluted with distilled water to prepare four working concentrations: 0.005%, 0.010%, 0.050%, and 0.200% (*w/v*), which were used as corrosion inhibitor solutions.

2.3. Electrochemical procedures

All electrochemical tests were implemented at room temperature using a conventional three-electrode electrochemical cell setup connected to a CHI660E electrochemical workstation (Fig. 3). A mild steel rod with a subjected surface area of 0.5024 cm^2 served as the working electrode. The working electrode was mild steel, with a chemical composition by weight of 98.977% Fe, 0.40900% Mn, 0.10200% Si, 0.08400% C, 0.07890% Ni, 0.06030% Cr, 0.21700% Cu, 0.01900% S, 0.01100% V, 0.01040% Mo,

0.01100% P, 0.01620% Sn, 0.00198% Co, and 0.00222% Nb. A platinum plate with a surface area of 2.0 cm² was used as a counter electrode, and an Ag/AgCl (3.0 M saturated KCl) electrode was used as a reference electrode.

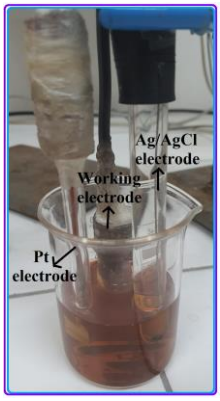


Figure 3. Conventional three-electrode immersion experimental setup in 0.200% (*w/v*) *Orbea variegata* +1.0 M HCl

Prior to each measurement, the Fe electrode was brightened using emery papers of varying grades (from 600 to 1000), rinsed with distilled water, degreased with acetone, and dried. The electrode was then immersed for 1 hour in 1.0 M HCl solution either with or without the extract before the electrochemical tests were carried out.

EIS was implemented over a frequency range of 10^5 Hz to $5x10^{-3}$ Hz with an amplitude of 5 mV. Data were collected in text file format and subsequently analysed via Zview2 software using appropriate equivalent circuit models. Potentiodynamic polarization tests were enrolled by sweeping the potential from ±350 mV versus open circuit potential (E_{corr}) at a scan rate of 1.0 $mV\,s^{-1}$. Corrosion current densities (i_{corr}) and inhibition efficiencies were derived using the Tafel extrapolation method.

2.4. Surface Morphology Analysis by FE-SEM

Field emission scanning electron microscopy (FE-SEM) analysis was performed to examine the surface morphology of mild steel after exposure to corrosive and inhibited environments. Mild steel samples were immersed for 1 hour in 1.0 M HCl solution in the absence and presence of the highest extract concentration (0.200% *w/v*). After immersion, the specimens were carefully degreased and rinsed with acetone and distilled water, dried in air, and examined using a Zeiss GeminiSEM 500 instrument. The resulting micrographs were used to visually assess the preservative effect of the plant extract on the metal surface.

3. Results and Discussion

3.1. Electrochemical Evaluation of Corrosion Inhibition

EIS is widely preferred in corrosion studies due to its high sensitivity to interfacial changes and its ability to provide detailed information on charge transfer and film resistance mechanisms without significantly disturbing the system under investigation (Sanni et al., 2024). In order to evaluate the corrosion inhibition performance of *Orbea variegata* extract, electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization techniques were realized following 1-hour immersion in 1.0 M HCl solution. The tests were conducted in the presence and absence of the extract at four concentrations (0.005%, 0.010%, 0.050%, and 0.200% *w/v*), and the corresponding inhibition efficiencies ($\eta\%$) were calculated based on the obtained electrochemical parameters. Zview2 software was used to create electrical equivalent circuit models based on the gathered EIS data in order to interpret the corrosion behaviour. Figure 4 indicates the impedance diagrams along with the different equivalent circuit models used for the blank (1.0 M HCl) and *Orbea variegata* extract-containing solutions after one hour of exposure to the aggressive solution.

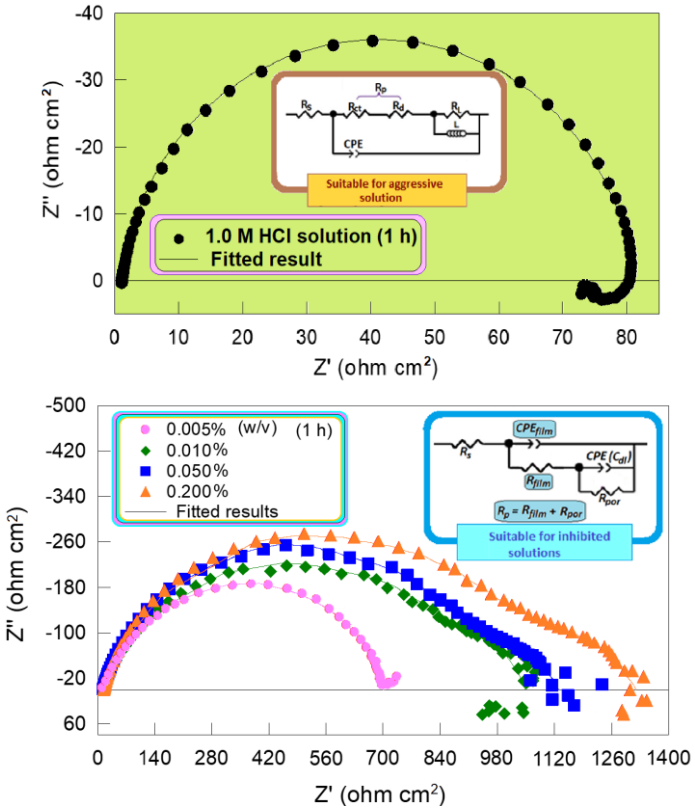


Figure 4. Electrical equivalent circuits and impedance diagrams used to model the EIS findings of mild steel electrodes in aggressive solution and containing *Orbea variegata* extract

The existence of *Orbea variegata* film-related characteristics is a crucial difference between these two models in Figure 4. Film resistance (R_f) and pore resistance (R_{por}), which are signs of adsorption by the *Orbea variegata* molecules, were introduced into the inhibited systems by the development of a preservative layer on the mild steel surface. On the other hand, when the inhibitor was not present, inductive components like inductive resistance (R_L) and inductance (L) were seen, although the diffuse

layer (R_d) and charge transfer resistances (R_{ct}) were mostly responsible for the polarisation resistance (R_p).

The EIS spectra displayed depressed capacitive semicircles in the Nyquist plots, indicating a non-ideal capacitive behaviour likely attributed to surface heterogeneity and adsorption of inhibitor molecules. A gradual increase in the diameter of the semicircles was observed with increasing extract concentration, reflecting enhanced charge transfer resistance (R_{ct}) (Figure 4). This suggests the formation of a more robust and adherent protective film on the mild steel surface (Aldahiri et al., 2025). All test solutions exhibit distinctive semi-circular profiles in the Nyquist diagrams, which is in line with a charge-transfer-controlled corrosion mechanism. As the concentration of *Orbea variegata* extract increased, a progressive increase in the semicircle's width was seen, suggesting that the *Orbea variegata* extract molecules were more strongly adsorbed on the iron surface. By forming a barrier layer, this adsorption prevents aggressive ionic species in the acidic media from transferring electrons to the metal substrate. The lack of inductive loops in the solutions containing *Orbea variegata* extract suggests that surface film resistance, rather than adsorbed intermediate species, is the primary governing factor in the main corrosion mechanism. Table 1 displays the EIS and Tafel extrapolation data obtained following Figures 4 and 5.

The highest polarization resistance (R_p) value was recorded as 1350 $\Omega\ cm^2$ at 0.200% concentration, with an inhibition efficiency of 94.7%, compared to 90.1% at 0.005%. This trend clearly demonstrates that the extract constituents interact with the metallic surface, bringing about an efficient suppression of charge transfer processes responsible for corrosion. The reduction in double-layer capacitance (C_{dl}) also confirms the adsorption of *Orbea variegata* molecules in the extract, which displace water and aggressive ions from the interface (Raja and Sethuraman, 2008). These findings align with previous studies on plant-based green inhibitors, where increasing concentration led to more durable and uniform adsorbed layers on metal surfaces (Umoren and Solomon, 2017; Miralrio and Espinoza Vázquez, 2020). Table 1 shows that the R_p values gradually increased as the concentration of *Orbea variegata* extract grew, while the values known as *CPE*, which represent the double layer between the metal and the substrate, decreased in tandem. As the concentration of the *Orbea variegata* extract increased, it was observed that the values denoted by "*n*" and known as the constant phase coefficient (surface inhomogeneity coefficient) likewise reduced.

Equations (1) and (2) express the calculation of $\eta\%$ and ${}^{*}\eta\%$ values from EIS and potentiodynamic polarization (Tafel extrapolation) methods, respectively (Özkır, 2024a; Özkır, 2024b).

$$\eta\% = \left(\frac{R'_p - R_p}{R'_p}\right) x100 \quad (1)$$

$${}^{*}\eta(\%) = \left(\frac{i_{corr} - i'_{corr}}{i_{corr}}\right) \times 100 \quad (2)$$

Table 1. EIS parameters in 1.0 M HCl solutions with and without *Orbea variegata* aqueous extract

***C* (*w/v* %)**	***EIS***							
Orbea variegata	E_{ocp} (*V*/Ag/AgCl)	R_s (Ω cm^2)	*CPE* (μF cm^{-2})	*n*	R_L (Ω cm^2)	*L* (*H*)	R_p (Ω cm^2)	η (%)
1.0 M HCl	-0.474	1.2	110	0.94	8	4	72	-
0.005	-0.511	1.3	95	0.74	-	-	726	**90.1**
0.010	-0.508	1.1	84	0.72	-	-	1035	**93.0**
0.050	-0.517	1.4	72	0.70	-	-	1130	**93.6**
0.200	-0.520	1.2	57	0.62	-	-	1350	**94.7**
Orbea variegata	**Potentiodynamic polarization (Tafel extrapolation method)*							
	E_{corr} (*V*/Ag/AgCl)	$-\beta_c$ (*mV* dec^{-1})	i_{corr} (μA cm^{-2})	$^*\eta$ (%)				
1.0 M HCl	-0.475	108	265	-				
0.005	-0.515	98	27	**89.8**				
0.010	-0.511	100	19	**92.8**				
0.050	-0.522	99	17	**93.6**				
0.200	-0.526	101	15	**94.3**				

The electrochemical behaviour of mild steel in 1.0 M HCl solution in the absence and presence of *Orbea variegata* extract was also examined by the potentiodynamic polarization technique, and the key electrochemical parameters are summarized in *Table 1. In the absence of the inhibitor, the corrosion potential (E_{corr}) was observed at –0.475 V (*vs. Ag/AgCl*), and the corrosion current density (i_{corr}) reached 265 $\mu A\ cm^{-2}$, reflecting intense corrosion activity in the acidic medium. The Tafel polarization curves in Figure 5 revealed that the addition of *O. variegata* extract significantly reduced i_{corr}, with a consistent decrease across all concentrations.

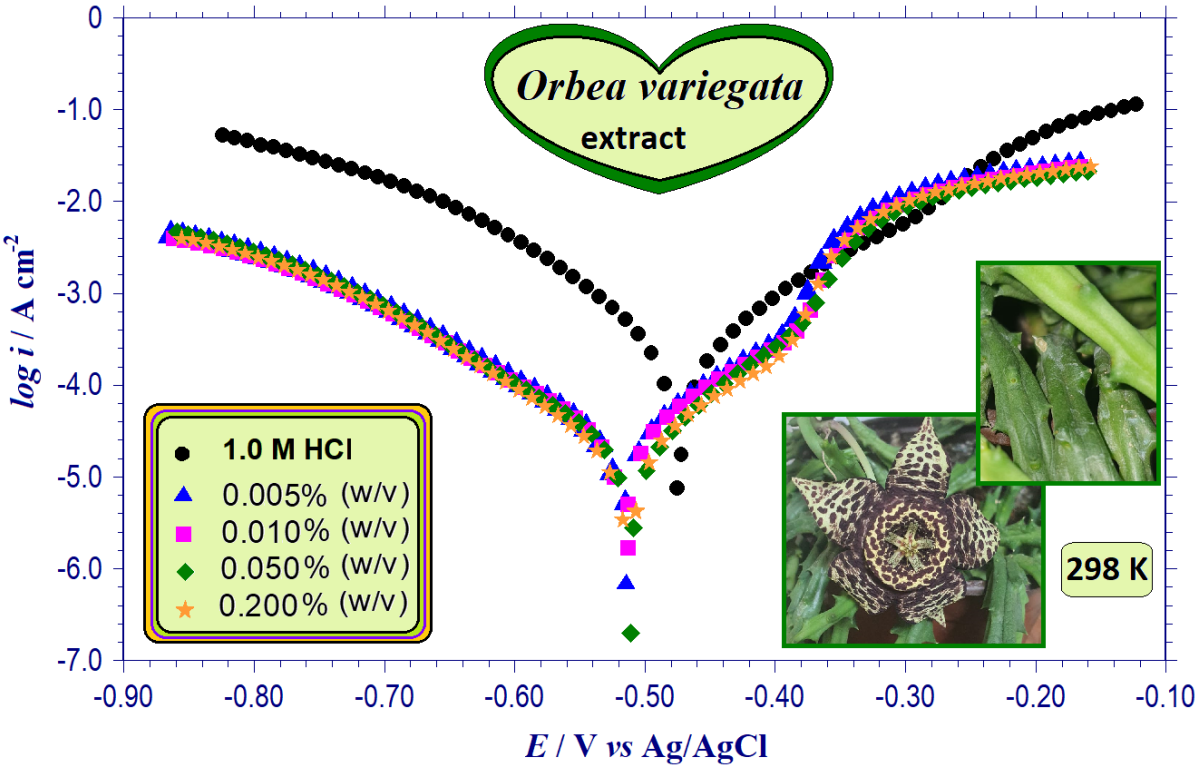


Figure 5. Overlapping Tafel polarization curves of mild steel electrodes in 1.0 M HCl as a function of *Orbea variegata* extract concentration

With the addition of the plant extract, there was a substantial and concentration-dependent decline in i_{corr} values. At the lowest concentration (0.005% *w/v*), i_{corr} decreased sharply to 27 $\mu A\ cm^{-2}$, corresponding to an inhibition efficiency of 89.8%. This trend continued with increasing extract concentrations, reaching a minimum value of 15 $\mu A\ cm^{-2}$ at 0.200%, with a corresponding maximum efficiency of 94.3%. These results indicate that the *Orbea variegata* extract effectively retards the electrochemical dissolution of mild steel in hydrochloric acid. A closer examination of the E_{corr} values reveals a shift from –0.475 V to –0.526 V with increasing inhibitor concentration, indicating a cathodic displacement. Despite this shift, suggesting that *Orbea variegata* extract acts primarily as a cathodic-type inhibitor, suppressing the hydrogen evolution reaction on the steel surface (Kumar et al., 2022). The cathodic Tafel slope ($-\beta_c$) values remained relatively stable, ranging between 98–101 $mV\ dec^{-1}$ in the presence of the *O. variegata* extract, compared to 108 $mV\ dec^{-1}$ in the uninhibited solution. This minor variation implies that the mechanism of the cathodic reaction remains unaltered, and the observed inhibition effect is mainly due to surface coverage by the extract molecules rather than a change in reaction pathway. The active phytochemical constituents likely adsorb preferentially at cathodic sites, blocking H^+ reduction reactions and reducing hydrogen gas evolution (Mashooque et al., 2022; Royani et al., 2024). Taken together, these polarization findings provide strong evidence that *Orbea variegata* extract functions as a predominantly cathodic corrosion inhibitor, with its efficiency being concentration-dependent. The enhanced inhibition at higher extract concentrations can be attributed to increased adsorption of phytochemical compounds containing functional groups such as hydroxyls, carbonyls, and aromatic rings capable of forming a protective barrier on the steel surface (Carmona-Hernandez et al., 2024).

3.2. FE-SEM Surface Analysis

To further support the electrochemical findings and provide insight into the physical alterations on the metal surface, FE-SEM analysis was performed on mild steel specimens immersed in 1.0 M HCl for 1 hour, both in the absence and presence of *Orbea variegata* extract at the highest tested concentration (0.200% *w/v*). The mentioned 200 times magnified surface morphologies are indicated to make a clearer comparison in Figure 6.

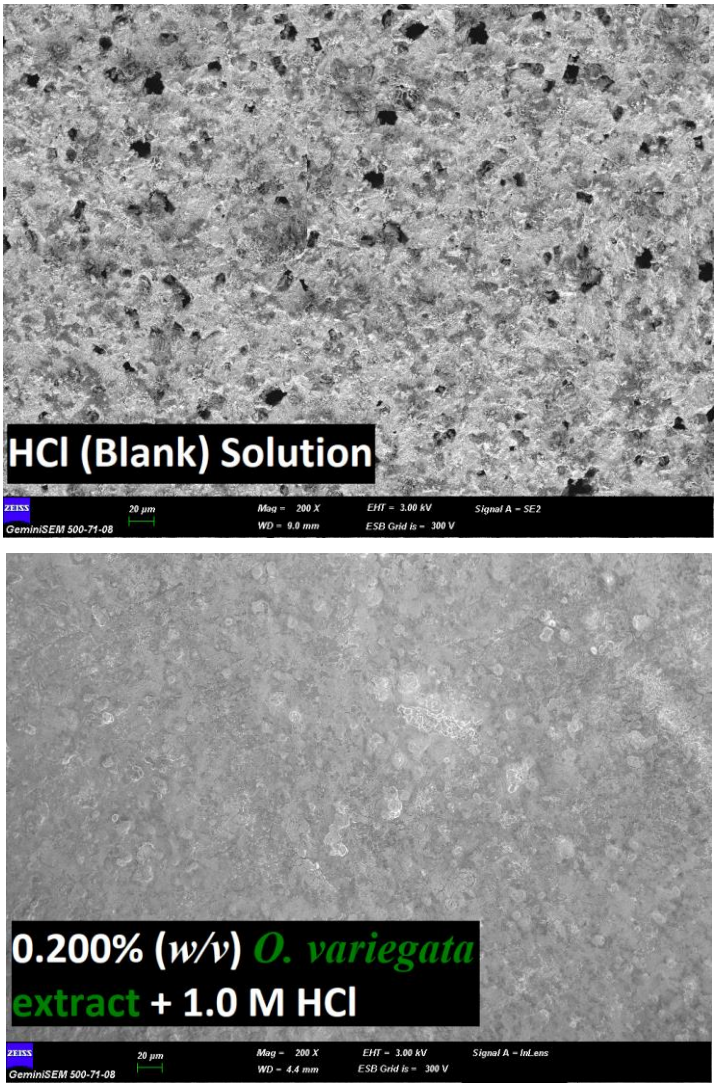


Figure 6. Surface analyses by FE-SEM in the absence and presence of *Orbea variegata* bio-inhibitor in HCl solution

The surface of the sample exposed to the uninhibited acidic solution exhibited clear signs of corrosion damage. As shown in the FE-SEM micrograph (Figure 6), the mild steel surface (blank solution) was severely roughened and covered with irregular pits and localized etching zones, characteristic of acid-induced corrosion in chloride media. The morphology confirmed that aggressive dissolution had taken place, resulting in a highly degraded topography with widespread surface disruption. In contrast, the surface of the mild steel specimen treated with the *O. variegata* extract (Figure 6) appeared significantly smoother and more uniform. The number and depth of corrosion pits were greatly reduced, and the metal surface exhibited a relatively continuous structure with fewer defects. This smoother morphology suggests that the extract formed a protective film over the steel surface, effectively mitigating direct acid attack. The protective layer likely originates from the adsorption of phytochemical constituents in the *O. variegata* extract, such as flavonoids and phenolics, which contain π-electrons and active functional groups capable of forming strong interactions with the metal surface (Hafazeh et al., 2025).

These observations align with the electrochemical data and confirm that *Orbea variegata* extract acts as a surface-active corrosion inhibitor. The constitution of a passive bio-inhibitor layer obstructs the access of corrosive species to the metal, thereby reducing localized attack and preserving the surface integrity.

4. Conclusion

This research represented that the aqueous extract of *Orbea variegata*, a succulent plant known locally as “carrion flower/cactus”, serves as a highly effective and sustainable corrosion bio-inhibitor for mild steel in 1.0 M HCl solution. Through a comprehensive electrochemical assessment including EIS and potentiodynamic polarization experiments, it was confirmed that the extract significantly reduced corrosion activity even at low concentrations. In particular, a 1-hour immersion period in the most concentrated extract solution (0.200% *w/v*) yielded inhibition efficiencies exceeding 94%, underscoring the rapid and potent protective action of the plant-derived compounds. Although the detailed chemical composition of *Orbea variegata* was not examined in this study, it is thought that its structure contains compounds rich in bioactive secondary metabolites such as flavonoids, phenolic acids, alkaloids and sterols, which are known to be abundant in all plants. These compounds typically contain hydroxyl, carbonyl, ether, and aromatic moieties and contain delocalized π-electron systems and heteroatoms such as P, O, S, and N, and they readily interact with the metal surface via physical adsorption or chemisorption. These interactions promote the formation of a protective molecular inhibitor film that inhibits the charge transfer processes essential for both anodic metal dissolution and cathodic hydrogen evolution. The FE-SEM surface analyses further supported the electrochemical results, clearly showing a marked difference in surface morphology between the uninhibited and inhibited specimens. The steel surface exposed to the blank HCl solution exhibited deep pits and irregular corrosion patterns, while the surface treated with *Orbea variegata* extract appeared smoother, indicating the presence of a coherent barrier layer that effectively prevented localized corrosion.

From a broader perspective, the utilization of *Orbea variegata* extract as a corrosion inhibitor is not only technically efficient but also environmentally meaningful. Derived from a renewable plant source, the extract is biodegradable, non-toxic, and water-soluble, offering a low-carbon-footprint alternative to conventional synthetic inhibitors. Its application aligns with the basis of “green chemistry and circular economy”, providing a dual benefit: preventing metallic degradation in aggressive environments and reducing the ecological burden associated with hazardous corrosion inhibitors.

In summary, the findings of this study highlight the untapped potential of *Orbea variegata* as a novel bio-inhibitor. Its high inhibition performance, rapid film formation, eco-compatibility, and cost-effectiveness position it as a promising candidate for sustainable corrosion protection strategies in industrial applications where hydrochloric acid is routinely used.

Compliance with ethical standards

The author declares that there is no conflict of interest.

Summary of researchers' contribution declaration

The author confirms sole responsibility for the entire content of the manuscript.

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