



Effect of Immersion Time on the Corrosion Behavior of Mild Steel in Sulfuric Acid with *Salvia officinalis* Inhibitor

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Abstract

This study investigates the impact of immersion time on the corrosion inhibition efficiency of *Salvia officinalis* (sage) essential oil extract for mild steel in 1 M H₂SO₄ by using the gravimetric (weight loss) method. Experiments were performed under constant conditions of inhibitor concentration, temperature, and acid concentration, with different exposure periods ranging from 12 to 72 hours. The results show that the inhibition efficiency of sage essential oil extract increases when immersion time is increased, reaching about 71% at 72 hours. The corrosion rate and weight loss of mild steel responded positively with the addition of inhibitor essential oil extract to 1.0 M H₂SO₄. A drop of almost 3 and 2.5 times less was achieved for corrosion rate and weight loss respectively. The results suggest that sage is a potent green inhibitor, and its performance improves over time due to a more favorable surface interaction, providing the ability to provide long-term protection for mild steel in acidic environments.

Paper Type: Research paper

Keywords: *Salvia officinalis* (sage), Immersion time, Mild steel, Green inhibitor, Corrosion rate.

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1. Introduction

The modern industrial sector faces corrosion as a major problem which results in substantial worldwide economic losses. The costs of steel corrosion prevention and treatment are unavoidable since ignoring proper protection methods causes systems and centers and other materials to deteriorate rapidly which makes them unusable within a short period (Tomić et al., 2016). Scientists and engineers have maintained corrosion control as their fundamental concern for many years. The most widely used strategy for corrosion prevention involves using corrosion inhibitors which include natural and inorganic substances (Ahmed et al., 2024). The use of inorganic inhibitors containing phosphates and chromates and heavy metals faces growing restrictions from environmental regulations. The discovery of toxic and environmental risks in numerous natural inhibitors has become a major concern. Research today focuses on creating "green" corrosion inhibitors which are both environmentally friendly and biocompatible. The rising complexity of the situation has driven numerous researchers to investigate the creation of safe and environmentally friendly corrosion inhibitors extracted from herbal resources including plant leaves and fruits and seeds (Al-Amiery et al., 2023).

Several published research papers by the scientific community have examined plant extracts as environmentally friendly corrosion inhibitors. Tannins, alkaloids, terpenoids, carbohydrates, proteins, and hydrolysis products are among the organic substances found in these extracts. Researchers have studied plant extracts to determine their effectiveness in preventing metal corrosion across different industrial settings (Fazal et al., 2022; Huang et al., 2022; Salleh et al., 2021; Zakeri et al., 2022). The attractiveness of these herbal inhibitors stems from their renewable origin, accessibility, low cost and minimal environmental impact.

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Sage (*Salvia officinalis* L.) represents a widely cultivated medicinal plant which holds traditional value in Jordanian and Levantine regions according to (Alsamosi, 2024). The plant contains numerous phytochemical compounds which make it useful for natural remedies and culinary preparation (Alsamosi, 2024).

Research has shown that sage contains diverse polyphenolic compounds which include diterpenoids together with flavonoids and various phenolic acids and their derivatives (Akrimi et al., 2025). The major phenolic compounds present in sage include carnosic acid together with rosmarinic acid and caffeic acid which demonstrate strong antioxidant and anti-inflammatory effects. The polyphenolic content of sage includes flavonoids together with luteolin and apigenin glycosides (luteolin-3-O-glycosides and luteolin-7-O-glycosides) and catechins (Miljanović et al., 2023). Recent research has focused on optimizing sage leaf polyphenol extraction by using modern extraction methods (Torres-Ortiz et al., 2023). The extraction methods studied include ultrasonic extraction (Babiker, 2024), microwave-assisted extraction (Zeković et al., 2017), high hydrostatic pressure strategy (Xi & Luo, 2016), and a combination of enzyme-assisted extraction and high-pressure treatment. The extraction methods include ultrasonic extraction and microwave-assisted extraction and high hydrostatic pressure strategies and enzyme-assisted extraction with high-pressure processing. The application of these strategies has gained popularity for the value creation of Jordanian medicinal plants in the pharmaceutical and nutritional and food industries (Fino et al., 2023). Multiple plant extracts from nature serve as environmentally friendly corrosion inhibitors which show promise for protecting defensive metals in acidic environments.

Research findings demonstrate that these extracts function as dual inhibitors which impact both anodic and cathodic processes. The protective properties of carbon steel are demonstrated by extracts obtained from prickly pear leaves (Wang et al., 2019), and ginger (Liu et al., 2019). Wild thyme protects 3014 chromium steel according to (Liu et al., 2019) and peppermint extracts and eucalyptus leaf extracts protect mild steel when exposed to acidic conditions (Dehghani et al., 2019; Nazari et al., 2023). The antioxidant properties of natural compounds together with green tea-derived compounds function as complex corrosion inhibitors (Pradipta et al., 2019). Plant extracts have shown protective effects on specific metals through their application on aluminum with pomegranate and lychee extracts (Gonzalez-Rodriguez et al., 2022), and iron with terebinth extracts (Barbouchi et al., 2020). The green corrosion inhibition of steel under acidic conditions is achieved through the use of sage (*Salvia officinalis*) leaf extract (Rasouli et al., 2020), and its essential oil (Dent et al., 2024). The duration of immersion strongly affects corrosion inhibitor performance particularly in severe acidic conditions (Shwetha et al., 2024). The time-dependent behavior of inhibitors depends on adsorption kinetics together with the stability of protective films on metal surfaces and the degradation or desorption of inhibitors throughout the exposure period (Jakeria et al., 2022).

Research findings demonstrate that immersion duration influences both corrosion rates and inhibition performance particularly when using plant-derived inhibitors (Medd, 2020). Li et al. (2019) examined radish (*Raphanus sativus*) leaf extract corrosion inhibition at low metal concentrations in 0.5 M H₂SO₄ solutions through gravimetric weight reduction analysis. The research examined different immersion durations starting from one hour up to 24 hours. The active phytochemicals absorbed into the system during the first two to three hours led to a minimal decrease in corrosion rate. The steel surface accumulated extract components which led to a substantial increase in inhibition efficiency reaching above 90% after 12 hours of immersion. The effect reached a peak at 12 hours before showing a minor decline. Natural compounds undergo increased thermal desorption and oxidative decomposition at longer exposure times and higher temperatures which leads to their degradation (Li, Zhang et al., 2019).

The corrosion inhibitory behavior of a fermentation extract of *Lachancea fermentati* -a yeast obtained from rotten grapefruit- was studied by (Tamilselvi et al., 2023) on a medium-hard metal in 1 M HCl solution for 72 hours. The bioactive compounds adsorbed onto the metal surface during the first 24 h caused the corrosion inhibitory effect to increase. The corrosion rate decreased substantially from 24 to 48 hours because the protective layer became thicker as confirmed by SEM and EIS. The protective layer remained solid and uniform after 72 hours with an inhibition efficiency of over 95% which demonstrated improved barrier properties and effective long-term corrosion protection (Tamilselvi et al., 2023).

This research examines the influence of time exposure on light metal corrosion behavior when immersed in 1.0 M H₂SO₄ solution with a set concentration of boiled sage plant extract. The study measured corrosion rate changes and inhibition capacity through gravimetric methods under constant test conditions across different time periods. The research findings will advance the creation of environmentally friendly corrosion protection techniques and establish sustainable methods for protecting light metals in acidic industrial settings.

2. Materials and Methods

2.1 Materials

Metal steel samples were obtained from the local market in Jordan. A fresh *Salvia officinalis* plant was picked from Irbid. Sulfuric acid (98%) and acetone (99.5%) were provided by Gainland Chemical Company, UK.

2.2 Inhibitor Extract Preparation

Salvia officinalis essential oil extract was prepared by refluxing 20g of the plant (leaves and stems) in 100ml of boiling deionized water for 24 hours. Afterward, the extract was separated from the plant to use as an inhibitor in the experiments.

2.3 Characterization Tests

X-ray Fluorescence (XRF) Analysis: Mild steel was selected for this study and was analyzed using a Sci-APS (X-200) handheld XRF analyzer to determine its elemental compositions. Its X-ray tube involves a rhodium anode operating at 50 kV (maximum voltage). The detector is a standard Silicon Drift Detector (SDD) with Mn-K α as a source of radiation (135eV spectral resolution).

Surface Morphology: A macro-level surface inspection was carried out using a smartphone camera equipped with 10x digital magnification of mild steel samples before the experiment, and also after immersion in the absence and presence of an inhibitor.

Proximate analysis: Before carrying out tests by the weight-dryer method, the dry material content was defined, and then constituents in the air-dry mass were tested. The proximate analysis of the *Salvia officinalis* were determined according to the Association of Official Analytical Chemists [AOAC] methods (Biel et al., 2023).

100 g fresh leaves of *Salvia officinalis* were collected locally from Irbid, Jordan. Distilled water was used to wash leaves to remove dust, afterwards leaves were air-dried at room temperature and then oven-dried at 60 °C until a constant weight was achieved. Dried leaves were ground and sieved (250 μ m mesh). A heat-resistant crucible was pre-weighed and approximately 2 g of the dried leaves was weighed into it, then the crucible was placed in a hot drying oven at 105 \pm 2 °C for 24 hours. afterwards crucible was cooled in a desiccator and reweighed. Moisture content was calculated according to Eq. (1):

$$\text{Moisture (\%)} = \left(\frac{W_1 - W_2}{W_1} \right) * 100 \quad (1)$$

W_1 : Initial weight of sample

W_2 : Weight of sample after drying

In order to calculate ash content, approximately 2 g of the dried sample was placed in a pre-weighed crucible and incinerated at 600 \pm 25 °C in a muffle furnace for 4 hours until a white ash was obtained, afterwards crucible was cooled in a desiccator and reweighed. Ash content was calculated using Eq. (2):

$$\text{Ash (\%)} = \left(\frac{W_3}{W_1} \right) * 100 \quad (2)$$

W_3 : Weight of ash

In order to calculate volatile matter, approximately 2 g of the dried sample was placed in a lidded pre-weighed crucible (crucible lid was used to limit oxygen exposure) and heated at 950 \pm 20 °C in a muffle furnace for 7 minutes. After cooling, the residue was weighed and volatile matter was calculated according to Eq. (3):

$$\text{Volatile Matter (\%)} = \left(\frac{W_1 - W_4}{W_1} \right) * 100 \quad (3)$$

W_4 : Weight after volatile matter removal

Fixed carbon was estimated by using Eq. (4):

$$\text{Fixed Carbon (\%)} = 100 - (\text{Moisture} + \text{Ash} + \text{Volatile Matter}) \quad (4)$$

Nutritional Tests: Various nutritional analysis were carried out on *Salvia officinalis* to determine its phytochemical constituents.

- Nutritional Composition Determination: Different types of nutritional compositions including total fat, Cholesterol, Carbohydrate, sugar, and protein were determined using the Foodscan Lab 78810 food analyzer, this analyzer works on the basis of Near-Infrared Reflectance spectroscopy. The analysis was conducted according to [AOAC] standard method (Nguyen et al., 2019).

Approximately 100 g of the sample were scanned using the device within the wavelength range of 850–1050 nm (this is the wavelength of the functional groups found in fats, cholesterol, sugar, carbohydrates, and protein).

- Mineral Composition Determination: Mineral content of the *Salvia officinalis* sample were determined using PerkinElmer AAnalyst 400, this device works with the principle of atomic absorption spectrometry (Flame Mode). The digestion process consists of weighing samples in crucibles, then raising the temperature stepwise to 350°C for 4 h, and then putting them in the oven at 550 °C for 16 h until a white ash. The ash was digested with acids heated until dry, followed by dissolution of the residue in boiling deionized water. The solution was then filtered through filter paper and introduced to the analyzer (Untea et al., 2012).

- Vitamins Determination: Vitamin content of *Salvia officinalis* was determined using high-performance liquid chromatograph (HPLC Shimadzu LC-20) with a UV detector at 280nm wavelength, and the mobile phase was consisting of methanol, water, and acetic acid (70:28:2, respectively) with a volumetric rate of 1 ml/min. An aqueous extract of *Salvia officinalis* was prepared to perform the analysis.

10 g of dried powdered leaves were macerated in 100 mL of distilled water for 30 min at 60°C. The extract was then cooled, and filtered prior to HPLC analysis.

Fourier Transform Infrared Spectroscopy (FTIR): *Salvia officinalis* functional groups spectra were obtained using Bruker Alpha II Compact FTIR Spectrometer with a Diamond Crystal ATR (Attenuated Total Internal Reflectance). The spectra were obtained at a wavenumber range of 400–4000 cm^{-1} with a resolution of 4 cm^{-1} . Samples were ground and dried in oven at 40 °C before FTIR analysis.

2.4 Weight Loss Method

Both the inhibition efficiency and Corrosion rates of this inhibitor were studied through the weight loss method. Initially, seven cleaned beakers were utilized and well labeled. After that, mild steel specimens were weighed with an analytical balance (4-digit) and then transferred to beakers. Afterwards, 500ml of H_2SO_4 (1M) is added to all beakers, followed by the addition of 30 ml (5.66% v/v) of inhibitor, except one to be as uninhibited stock samples. All mild steel specimens were completely immersed. At room temperature, samples were left for different immersion intervals as follows: 12, 24, 36, 48, 60, 72hrs. At the end of each interval, specimens were washed with acetone, desiccated in air, and reweighed.

Inhibition efficiency (%IE) and corrosion rate (CR) are estimated using Eqs. (5) and (6):

$$\%IE = \left(1 - \left(\frac{W_2}{W_1}\right)\right) * 100\% \quad (5)$$

$$CR = \frac{\Delta W}{A * t} \quad (6)$$

Where (W_1 and W_2) denote weight loss in the absence and presence of the inhibitor, (ΔW) refers to the difference in weight loss in the presence and absence of the inhibitor, (A) indicates the specimen's surface area, and (t) refers to immersion time.

3. Results and discussion

3.1 Mild steel characterization

3.1.1 Chemical composition

The mild steel used in this study was characterized using Sci-APS device (X-200) -portable XRF analytical instrument- to determine its chemical composition. Results in **Table 1** revealed a typical composition consistent with commercial low-carbon steel grades.

Table 1. Chemical composition of mild steel (mass %) (Al-Btoush et al., in press)

Chemical Elements	Fe	Mn	Si	S	Cu	Ni	C
Mass %	99.13	0.489	0.163	0.1	0.063	0.034	0.025

3.1.2 Surface Morphology

Surface examination analysis was conducted to assess the protective effect of *Salvia officinalis* essential oil extract on mild steel in acidic solution. Three sample conditions were analyzed: (a) unexposed mild steel **Figure 1**, (b) mild steel immersed in 1 M of H_2SO_4 solution **Figure 2**, and (c) mild steel immersed in 1 M of H_2SO_4 solution containing *Salvia officinalis* essential oil extract **Figure 3**. A Smartphone camera equipped with super macro digital magnification was used for this surface examination. As shown in **Figure 1**, the mild steel nail surface appears shiny with notable irregularities, including visible roughness. These features are typical characteristics of low-cost, low-carbon steel which is usually marketed without polishing after basic mechanical processing such as wire drawing or rolling. Some areas showed early-stage surface oxidation, expected to be caused by atmospheric corrosion such as exposure to moisture or humid conditions. No visible rust or corrosion products are present. This confirms that the sample was clean serving as a baseline reference. As seen in **Figure 2**, mild steel immersed in 1 M of H_2SO_4 solution for (48 hrs) showed extensive corrosion attack which is justified by the heavy corrosion effect of acid within long immersion time as well as lack of protective layer or galvanization. The surface showed significant discoloration and a dark reddish-brown corrosion product (iron oxides). On the other hand, as shown in **Figure 3**, mild steel immersed in 1 M of H_2SO_4 solution with the presence of inhibitor essential oil extract for (48 hrs) showed minor change compared to the baseline reference sample shown in **Figure 1** except of discoloration. The surface lost shininess and was darker than the baseline reference sample but lacked the heavy rust appearance and corrosion products seen in **Figure 2**, indicating successful protection film formation by the used green inhibitor on the surface of mild steel which slowed the corrosion reaction, and restricted the interaction between the mild steel surface and sulfate ions in the solution. Surface morphology observations are shown in **Table 2**.

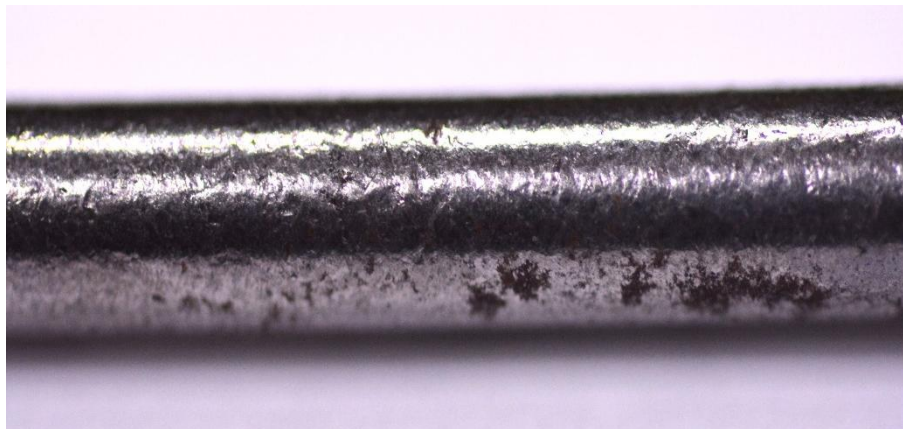


Fig. 1. Mild steel before immersion.



Fig. 2. Mild steel after immersion in 1 M of H₂SO₄ only (48 hrs).



Fig. 3. Mild steel after immersion in 1 M of H₂SO₄ with essential oil extract included (48 hrs).

Table 2. Surface morphology observations

Sample Condition	Surface Description	Corrosion Features	Protection Assessment
Unexposed mild steel	Rough, shiny metallic surface	No visible corrosion	No protection needed
Mild steel immersed in 1 M H ₂ SO ₄	Rough, darkened surface with reddish-brown corrosion layer	Heavy corrosion with visible rust formation	No protection; full acid attack
Mild steel immersed in 1 M H ₂ SO ₄ with <i>Salvia</i> essential oil	Moderately darkened, more uniform surface; reduced visible roughness with no visible corrosion products	Minor corrosion signs; surface less degraded compared to uninhibited sample	Good protection; effective inhibitor action observed

3.2 *Salvia officinalis* characterization

3.2.1 ATR-FTIR Analysis of *Salvia officinalis*

Attenuated Total Reflectance Fourier-Transform Infrared (ATR-FTIR) spectroscopy was employed to identify the functional groups of *Salvia officinalis*. These groups should be responsible for interacting with the mild steel surface forming a protective layer against any corrosion reactions. The ATR-FTIR spectrum of *Salvia officinalis* **Figure 4** revealed several characteristic absorption bands that support the presence of organic functional groups associated with corrosion inhibition. A broad peak observed in the region $\sim 3300\text{ cm}^{-1}$ corresponds to the O–H stretching vibrations of phenolic and alcoholic compounds. These molecules are known to play a key role in surface adsorption onto mild steel (Dent et al., 2024). Significant peaks detected near $2920\text{--}2850\text{ cm}^{-1}$ are attributed to C–H stretching vibrations of aliphatic $-\text{CH}_2$ and $-\text{CH}_3$ groups, likely from terpenes and essential oil constituents. These hydrophobic components contribute to the formation of a compact organic layer that limits metal–acid contact (Rhaimi et al., 2022). An absorption band around 1720 cm^{-1} is assigned to C=O stretching vibrations, indicating the presence of carbonyl groups from esters or carboxylic acids, which can coordinate with Fe^{2+} or Fe^{3+} ions on the steel surface. Additional peaks at approximately 1600 cm^{-1} reflect C=C stretching vibrations from aromatic rings, supporting the presence of flavonoid-like compounds. Moreover, the bands detected near $1100\text{--}1030\text{ cm}^{-1}$ are attributed to C–O stretching of alcohols, ethers, or phenolic groups. These oxygen-rich groups enhance adsorption through interactions with the surface of the metal (Dent et al., 2024). Overall, the ATR-FTIR results confirm that *Salvia officinalis* contains multiple functional groups—hydroxyl, carbonyl, aliphatic, and aromatic systems—that facilitate its action as a green corrosion inhibitor. These findings align with previous studies which demonstrated that such phytochemicals adsorb onto the steel surface and reduce corrosion by forming a protective film (Rhaimi et al., 2022; Dent et al., 2024). A Summary of ATR-FTIR results is shown in **Table 3**.

Table 3. ATR-FTIR functional groups identified in *Salvia officinalis*

Wavenumber (cm ⁻¹)	Functional Group	Chemical Assignment	Corrosion Inhibition Role
~ 3300	O–H stretch	Phenols / Alcohols	Promote adsorption onto steel via hydrogen bonding or coordination
$2920 - 2850$	C–H stretch	Aliphatic chains (CH ₂ , CH ₃ in terpenoids or oils)	Enhance surface coverage and barrier formation
~ 1720	C=O stretch	Carbonyl groups (carboxylic acids, esters)	Form complexes with $\text{Fe}^{2+}/\text{Fe}^{3+}$ ions; support chemisorption
~ 1600	C=C stretch	Aromatic rings / Flavonoid structures	Enhance molecular adsorption
$1100 - 1030$	C–O stretch	Ethers, alcohols, glycosides, phenolic esters	Enhance physical and chemical adsorption

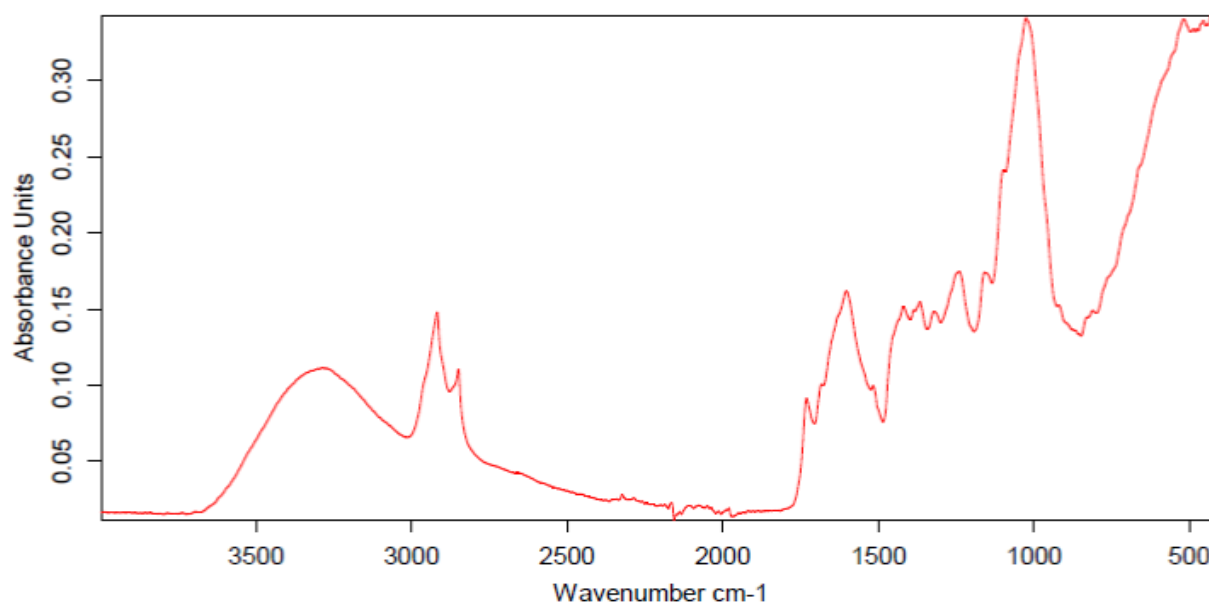


Fig. 4. ATR-FTIR spectra of *Salvia officinalis*.

3.2.2 Nutritional Composition of *Salvia officinalis*

The food analyzer results are shown in **Table 4**, consisting of 12.3% total fat, 42% carbohydrate, 41% dietary fat. These nutrients contain functional groups capable of interacting with the metal surface, aiding corrosion inhibition.

Table 4. Nutritional composition of *Salvia officinalis* powder (Al-Btoush et al., in press)

Composition	g/100g
Total Fat	12.3
Saturated Fat	0
Trans Fat	0
Polyunsaturated Fat	0
Monounsaturated Fat	0
Cholesterol	0
Sodium	0
Carbohydrate	42
Dietary Fat	41
Sugar	0
Protein	0

3.2.3 Mineral Content of *Salvia officinalis*

Table 5 summarizes minerals detected in *Salvia officinalis*. Calcium, potassium, and magnesium were found in significant quantities (Ca: 1200 mg/100g, K: 630 mg/100g, Mg 305 mg/100g), along with traces of iron (22 mg/100g), zinc (4.2 mg/100g), and manganese (1.5 mg/100g). These minerals may influence the inhibitor's surface adsorption properties or contribute to complexation on the metal interface.

Table 5. Mineral content of *Salvia officinalis* (Al-Btoush et al., in press)

Composition	mg/100g
Calcium	1200
Potassium	630
Magnesium	305
Iron	22
Zinc	4.2
Manganese	1.5

3.2.4 Vitamin content of *Salvia officinalis*

HPLC analysis of *Salvia officinalis* shown in **Table 6** identified vitamin A (0.9 mg/100g), vitamin C (21 mg/100g), vitamin E (9 mg/100g), thiamin (0.07 mg/100g), niacin (6 mg/100g), folate (0.13 mg/100g), and vitamin B6 (1.2 mg/100g). These bioactives contribute antioxidant properties and can adsorb onto mild steel, protecting it from acid attack.

Table 6. Vitamin content of *Salvia officinalis* (Al-Btoush et al., in press)

Composition	mg/100g
Vitamin A	0.9
Vitamin C	21
Vitamin E	9
Thiamin	0.07
Niacin	6
Folate	0.13
Vitamin B6	1.2

3.2.5 Proximate Composition of *Salvia officinalis*

The results of the proximate analysis of *Salvia officinalis* are presented in **Table 7**. The sample exhibits very low moisture and ash contents, high volatile matter, and low fixed carbon.

Table 7. Proximate composition of *Salvia officinalis* (Al-Btoush et al., in press)

	Moisture	Volatile Matter	Fixed Carbon	Ash
wt%	3.1	92.1	5.0	2.9

The moisture content of *Salvia officinalis* was found to be 3.1%, well below the recommended maximum of 10-14% for dried plant materials (Tibor & Evelin, 2017). Low moisture ensures chemical stability of sage bioactive compounds in storage, minimizing degradation before extraction.

The volatile matter was exceptionally high at 92.1%, indicating a dominant presence of organic compounds such as essential oils, flavonoids, terpenes, and phenolic acids which are known contributors to corrosion inhibition (Hana *et al.*, 2017). These compounds typically contain functional groups (e.g., -OH, -OCH₃, -COOH) that prevent corrosion by forming a protective layer as they adsorb onto the mild steel surface.

3.3 Effect of Immersion Time on Inhibition Efficiency

Weight loss experiments were conducted for mild steel immersed in 1 M H₂SO₄ with 5.66% v/v (30 ml) of *Salvia officinalis* essential oil extract at room temperature 22 ± 1°C. The inhibition efficiency was calculated accordingly and showed a consistent increase as immersion time was extended, revealing the dynamic nature of inhibitor adsorption and surface film formation. Starting at 26% at 12 hours, inhibition efficiency increased gradually reaching an impressive maximum value of 71% at 72 hours, which corresponds to a saturation coverage of inhibitor components on the steel surface. These results signify that immersion time has an impact on inhibition efficiency and highlight the critical role of immersion time in optimizing inhibitor performance, which correlates with findings of similar investigations done by (Murthy & Vijayaragavan, 2014). The results are shown in **Figure 5**.

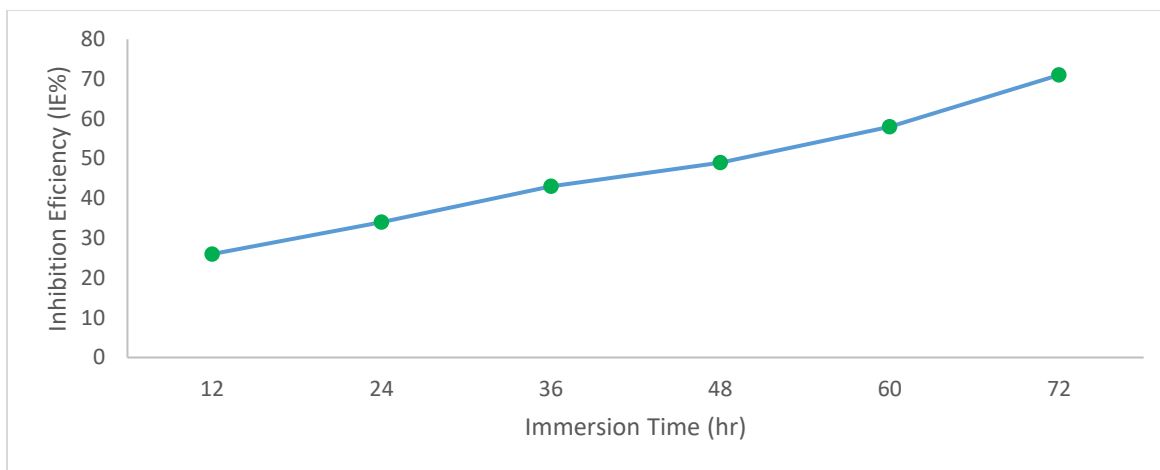


Fig. 5. Inhibition efficiency of *Salvia officinalis* extract at different immersion times.

3.4 Effect of Immersion Time on Corrosion Rate and Weight Loss

The corrosion rate is a direct measure of the extent of metal deformation in the aggressive sulfuric acid environment. Observing uninhibited mild steel samples, the corrosion rate was consistently high at early immersion time (2.2 mg/cm²·hr at 12 hours of immersion time) confirming the highly corrosive nature of 1.0 M H₂SO₄. This high corrosion rate is justified by the mild steel surface cleanliness and full exposure to the acid at the beginning of the reaction, therefore the absence of any protective layer. After 24 hours of immersion time the corrosion rate started to decrease as immersion time increases, this decrement in corrosion rate is caused by corrosion reaction byproducts that accumulate on the mild steel surface acting as a kind of barrier that slows down corrosion rate at which the acid has more difficulty reaching the metal. At late immersion times, corrosion rates reached almost steady values at which corrosion reactions reach a kind of equilibrium. Upon introducing the green inhibitor, a significant reduction in corrosion rate was observed, demonstrating the effective adsorption of inhibitor components on the steel surface, especially at extended immersion time (Quraishi et al., 2000). A significant drop in corrosion rate with the use of an inhibitor was observed -almost 3 times less at 72 hours of immersion time- compared to that without the presence of an inhibitor, reaching 0.25 mg/cm²·hr at 72 hours of immersion time -with inhibitor- while it was 0.72 mg/cm²·hr at the same immersion time -without inhibitor-. **Figure 6** shows the results.

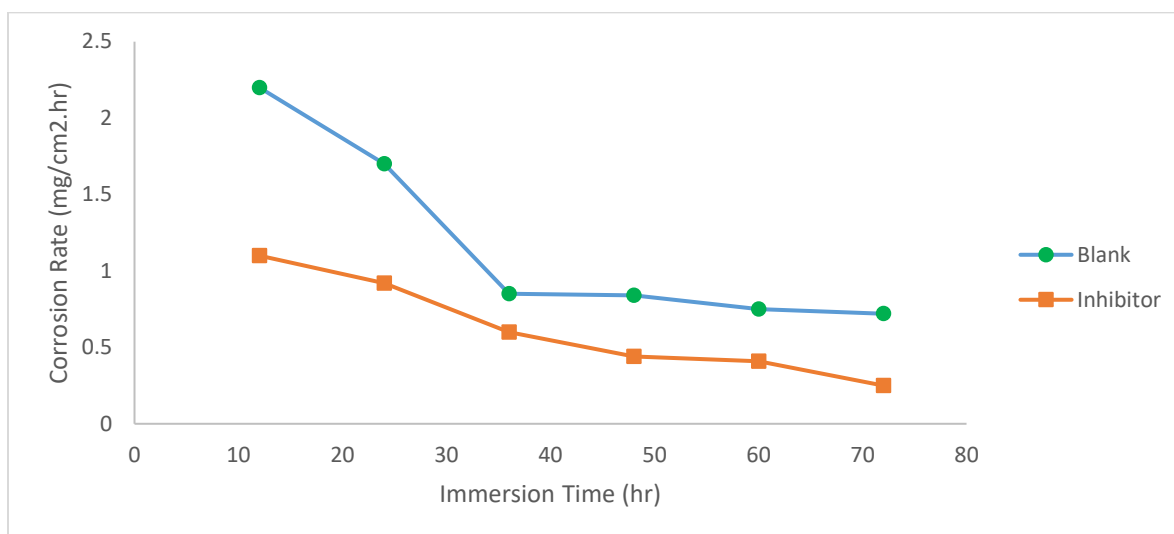


Fig. 6. Corrosion rate of mild steel in 1.0 M H₂SO₄ with and without inhibitor at different immersion times.

Normally weight loss increases with time, this is justified by the dissolution of some amount of steel as long as the mild steel is exposed to acid. In this study, weight loss increased with time normally but showed an impressive interaction with the addition of *Salvia officinalis* essential oil extract as an inhibitor to the acidic media. Weight loss with the presence of inhibitor was -almost 2.5 times less at 72 hours of immersion time - compared to the same sample immersed in 1.0 M H₂SO₄ without the presence of inhibitor. A weight loss of 270 mg at 72 hours of immersion time was reached with the use of the inhibitor while it was 645 mg without the use of the inhibitor at the same immersion time, as shown in **Figure 7**.

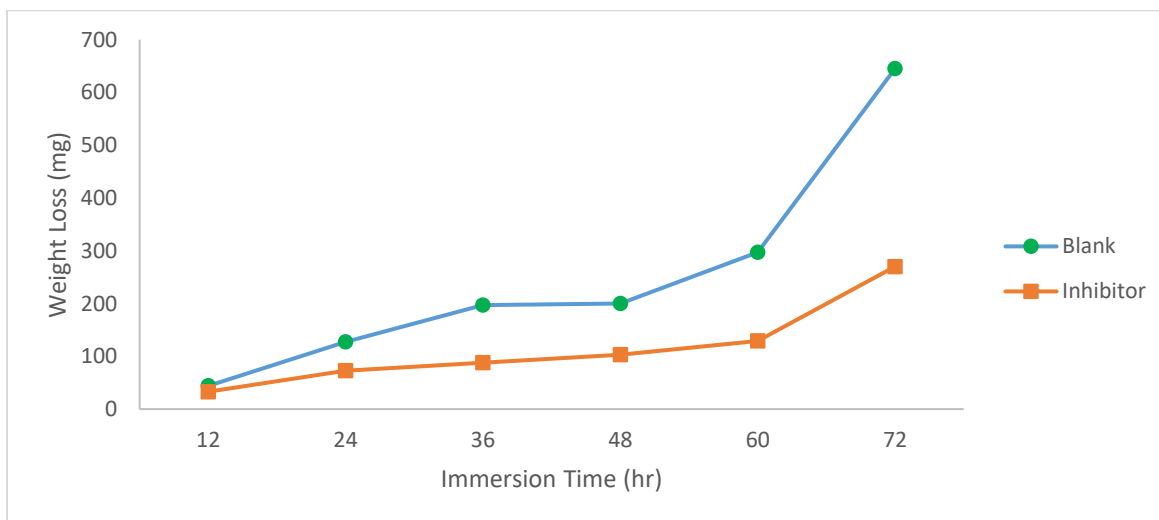


Fig. 7. Weight loss of mild steel in 1.0 M H₂SO₄ with and without inhibitor at different immersion times.

A general comparison of the inhibition efficiency of other green inhibitors at the same immersion time is shown in **Table 8**. Differences in inhibition efficiencies among plant extracts may be referred to variations in active components (e.g., flavonoids, alkaloids, tannins) of each plant, as well as the plant extract concentration used for inhibition. **Note:** comparison shown in **Table 8** is general as the test conditions were different.

Table 8. Comparison of inhibition efficiency of various green inhibitors in acidic media

Green Inhibitor	Acidic Medium	Inhibitor Concentration	Immersion Time (h)	Inhibition Efficiency (%)	Reference
<i>Salvia officinalis</i>	1.0 M H ₂ SO ₄	5.66% v/v	24	34	Present study
<i>Hibiscus sabdariffa</i>	1.2 M H ₂ SO ₄	2g/100ml	24	73	(Murthy & Vijayaragavan, 2014)
<i>Hibiscus sabdariffa</i>	1.2 M HCl	2g/100ml	24	51	(Murthy & Vijayaragavan, 2014)

3.5 Practical and Economic Implication

Salvia officinalis extract have an economic advantage because of its low-cost, simple extraction process, and local availability. Unlike synthetic inhibitors that require more complex synthesis and special environmental handling procedures. This makes it a promising alternative for traditional chemical corrosion inhibitors.

4. Conclusions

Results clearly demonstrate that immersion time influences the corrosion protection ability of *Salvia officinalis* essential oil extract for mild steel in an acidic environment such as 1.0 M H₂SO₄ if it is applied within the proper conditions. The inhibitor's performance was evaluated following the weight loss measurement technique. Inhibition efficiency increased gradually with increasing immersion time. The immersion time was found to have a significant impact on both corrosion rates and weight loss. Key findings are summarized as follows:

1. Increasing the immersion time of mild steel in 1.0 M H₂SO₄ with the presence of *Salvia officinalis* essential oil extract significantly enhanced corrosion inhibition efficiency. The inhibition efficiency was 26% at 12 hours and reached 71% at 72 hours, with an inhibitor concentration of 5.66% v/v (30ml).
2. The corrosion rate and weight loss of mild steel responded positively with the addition of inhibitor extract to 1.0 M H₂SO₄. A drop of almost 3 & 2.5 times less was achieved for corrosion rate and weight loss respectively.

CRedit Author Contributions

M. A. Al-Awamleh: Conceptualization, Writing – Review & Editing, Resources, Visualization, Supervision, Project Administration.

S. H. Aljbour: Supervision, Project Administration.

S. N. Badarneh: Methodology, Investigation, Writing – Original Draft, Visualization.

T. T. Al-Btoush: Methodology, Investigation, Writing – Original Draft, Visualization.

Declaration Statements

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Conflicts of Interest

The authors declare no conflict of interest.

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Nomenclature

Abbreviation	Full Term
AOAC	Association of Official Analytical Chemists
ATR	Attenuated Total Reflectance
EIS	Electrochemical Impedance Spectroscopy
FTIR	Fourier Transform Infrared Spectroscopy
HPLC	high-performance liquid chromatograph
SDD	Silicon Drift Detector
SEM	Scanning Electron Microscopy
UV	Ultraviolet
XRF	X-Ray Florescence

References

- Abu-Odeh, A., Fino, L., Al-Absi, G., Alnatour, D., Al-Darraj, M., Shehadeh, M., & Suaifan, G. (2023). Medicinal plants of Jordan: Scoping review. *Heliyon*, 9(6). <https://doi.org/10.1016/j.heliyon.2023.e17081>
- Ahmed, M. A., Amin, S., & Mohamed, A. A. (2024). Current and emerging trends of inorganic, organic and eco-friendly corrosion inhibitors. *RSC Advances*, 14(43), 31877–31920. <https://doi.org/10.1039/D4RA05662K>
- Akrimi, H., Jerbi, A., Elghali, F., Mnif, S., Aifa, S., Fki, L., & Kammoun, M. (2025). Investigation of the bioactive properties of Tunisian sage extracts: A detailed analysis of phytochemical composition and their antioxidant, antibacterial, and antibiofilm activities. *Chemistry Africa*, 8, 1351–1363. <http://doi.org/10.1007/s42250-025-01240-0>
- Al-Amiery, A. A., Isahak, W. N. R. W., & Al-Azzawi, W. K. (2023). Corrosion inhibitors: Natural and synthetic organic inhibitors. *Lubricants*, 11(4), 174. <http://doi.org/10.3390/lubricants11040174>
- Al-Btoush, T. T., Aljbour S. H., Al-Awamleh M. A., & Badarneh S. N. (in press). Investigation of *Salvia officinalis* as a natural corrosion inhibitor for mild steel in sulfuric acid. *Research Journal of Chemistry and Environment*.
- Alsamosi, S. M. (2024). Sage (*Salvia officinalis*), known as "Maramia" in Arabic culture: An overview and herbal monograph. *Pharmacognosy Research*, 16(3), 467–471. <http://doi.org/10.5530/pres.16.3.56>
- Babiker, M. E. (2024). Experimental and computational study of *Salvia officinalis* leaf extract as an eco-friendly green corrosion inhibitor for zinc in 0.5 M sulfuric acid solution. *The International Journal of Corrosion and Scale Inhibition*, 13(3), 1777–1796. <http://doi.org/10.17675/2305-6894-2024-13-3-25>
- Barbouchi, M., Benzidia, B., Aouidate, A., Ghaleb, A., El Idrissi, M., & Choukrad, M. b. (2020). Theoretical modeling and experimental studies of Terebinth extracts as green corrosion inhibitor for iron in 3% NaCl medium. *Journal of King Saud University-Science*, 32(7), 2995–3004. <http://doi.org/10.1016/j.jksus.2020.08.004>
- Biel, W., Pomietło, U., Witkiewicz, R., Piątkowska, E., & Kopeć, A. (2023). Proximate composition and antioxidant activity of selected morphological parts of herbs. *Applied Sciences*, 13(3), 1413. <https://doi.org/10.3390/app13031413>
- Dehghani, A., Bahlakeh, G., & Ramezanzadeh, B. (2019). Green Eucalyptus leaf extract: A potent source of bio-active corrosion inhibitors for mild steel. *Bioelectrochemistry*, 130, 107339. <https://doi.org/10.1016/j.bioelechem.2019.107339>
- Dent, M., Fuchs-Godec, R., Pedisić, S., Grbin, D., Dragović-Uzelac, V., Ježek, D., & Bosiljkov, T. (2024). Polyphenols from sage leaves (*Salvia officinalis* L.): Environmentally friendly extraction under high hydrostatic pressure and application as a corrosion inhibitor for tinplate. *Separations*, 11(5), 158. <https://doi.org/10.3390/separations11050158>
- Fazal, B. R., Becker, T., Kinsella, B., & Lepkova, K. (2022). A review of plant extracts as green corrosion inhibitors for CO₂ corrosion of carbon steel. *NPJ Materials Degradation*, 6, 5. <https://doi.org/10.1038/s41529-021-00201-5>
- Hana, K., Khadraoui, A., Hachama, K., Karim, S., Serdaroğlu, G., Aouniti, A., & Kaya, S. (2017). An overview on plant extracts as potential green corrosion inhibitors for metals and alloys. *Arabian Journal of Chemical and Environmental Research*, 4(1), 46–62.
- Huang, L., Chen, WQ., Wang, S.S., Zhao, Q., Li, HJ., & Wu, YC. (2022). Starch, cellulose and plant extracts as green inhibitors of metal corrosion: a review. *Environmental Chemistry Letters*, 20, 3235–3264. <https://doi.org/10.1007/s10311-022-01400-5>
- Jakeria, M. R., Toh, R. J., Chen, X.-B., & Cole, I. S. (2022). Evolution and stability of 2-mercaptobenzimidazole inhibitor film upon Al alloy 6061. *Journal of Applied Electrochemistry*, 52(6), 1021–1044. <https://doi.org/10.1007/s10800-022-01687-w>
- Li, D., Zhang, P., Guo, X., Zhao, X., & Xu, Y. (2019). The inhibition of mild steel corrosion in 0.5 M H₂SO₄ solution by radish leaf extract. *RSC Advances*, 9(70), 40997–41009. <https://doi.org/10.1039/c9ra04218k>
- Liu, Y., Song, Z., Wang, W., Jiang, L., Zhang, Y., Guo, M., Song, F., & Xu, N. (2019). Effect of ginger extract as green inhibitor on chloride-induced corrosion of carbon steel in simulated concrete pore solutions. *Journal of Cleaner Production*, 214, 298–307. <https://doi.org/10.1016/j.jclepro.2018.12.299>
- Medd, R. J. (2020). Conversations with planet ocean: Plastic pollution and the common heritage of humankind. *Cross Cultural Studies Review: A Journal for Comparative Studies of Culture, Literature, and the Arts*, 2(3-4), 83–142. <https://doi.org/10.38003/ccsr.2.1-2.5>

- Miljanović, A., Dent, M., Grbin, D., Pedisić, S., Zorić, Z., Marijanović, Z., Jerković, I., & Bielen, A. (2023). Sage, rosemary, and bay laurel hydrodistillation by-products as a source of bioactive compounds. *Plants*, *12*(13), 2394. <https://doi.org/10.3390/plants12132394>
- Murthy, Z., & Vijayaragavan, K. (2014). Mild steel corrosion inhibition by acid extract of leaves of Hibiscus sabdariffa as a green corrosion inhibitor and sorption behavior. *Green Chemistry Letters and Reviews*, *7*(3), 209–219. <https://doi.org/10.1080/17518253.2014.924592>
- Nazari, A., Ramezanzadeh, B., Guo, L., & Dehghani, A. (2023). Application of green active bio-molecules from the aquatic extract of mint leaves for steel corrosion control in hydrochloric acid (1M) solution: Surface, electrochemical, and theoretical explorations. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *656*(B), 130540. <https://doi.org/10.1016/j.colsurfa.2022.130540>
- Nguyen, N., Jacobs, M., Li, J., Huang, C., Li, D., Navarro, D. M., Stein, H., H., & Jaworski, N. W. (2019). Concentrations of soluble, insoluble, and total dietary fiber in feed ingredients determined using method AOAC 991.43 are not different from values determined using method AOAC 2011.43 with the AnkomTDF dietary fiber analyzer. *Journal of Animal Science*, *97*(9), 3972–3983. <https://doi.org/10.1093/jas/skz239>
- Poós, T., & Varju, E. (2017). Drying characteristics of medicinal plants. *International Review of Applied Sciences and Engineering*, *8*(1), 83-91. <https://doi.org/10.1556/1848.2017.8.1.12>
- Pradipta, I., Kong, D., & Tan, J. B. L. (2019). Natural organic antioxidants from green tea inhibit corrosion of steel reinforcing bars embedded in mortar. *Construction and Building Materials*, *227*, 117058. <https://doi.org/10.1016/j.conbuildmat.2019.117058>
- Quraishi, M., Rawat, J., & Ajmal, M. (2000). Dithiobiurets: A novel class of acid corrosion inhibitors for mild steel. *Journal of Applied Electrochemistry*, *30*, 745–751. <https://doi.org/10.1023/A:1004099412974>
- Rasouli, B., Movahhedkhal, S., Seidavi, A., Haq, Q. M. I., Kadim, I., Laudadio, V., Mazzei, D., & Tufarelli, V. (2020). Effect of sage (*Salvia officinalis* L.) aqueous leaf extract on performance, blood constituents, immunity response and ileal microflora of broiler chickens. *Agroforestry Systems*, *94*, 1179–1187. <https://doi.org/10.1007/s10457-019-00401-8>
- Rhaimi, S., Ouakki, M., Rhaïem, N., Galai, M., Dahmani, K., El Farhani, F., & Touhami, M. E. (2022). *Salvia officinalis* essential oil as green corrosion inhibitor for mild steel in acidic media. *International Journal of Chemical and Biological Sciences*, *21*, 272–280.
- Salleh, S. Z., Yusoff, A. H., Zakaria, S. K., Taib, M. A. A., Abu Seman, A., Masri, M. N., Mohamad, M., Mamat, S., Sobri, S., A., Ali, A., & Teo, P. T. (2021). Plant extracts as green corrosion inhibitor for ferrous metal alloys: A review. *Journal of Cleaner Production*, *304*, 127030. <https://doi.org/10.1016/j.jclepro.2021.127030>
- Shwetha, K., Praveen, B., & Devendra, B. K. (2024). A review on corrosion inhibitors: Types, mechanisms, electrochemical analysis, corrosion rate and efficiency of corrosion inhibitors on mild steel in an acidic environment. *Results in Surfaces and Interfaces*, *16*, 100258. <https://doi.org/10.1016/j.rsufi.2024.100258>
- Tamilselvi, B., Bhuvaneshwari, D. S., Karuppasamy, P., Padmavathy, S., Nikhil, S., Siddegowda, S. B., & Ananda Murthy, H. (2023). Investigation of corrosion inhibition of mild steel in 0.5 M H₂SO₄ with *Lachanea fermentati* inhibitor extracted from rotten grapefruits (*Vitis vinifera*): Adsorption, thermodynamic, electrochemical, and quantum chemical studies. *ACS Physical Chemistry Au*, *4*(1), 67–84. <https://doi.org/10.1021/acsphyschemau.3c00055>
- Tomić, M. V., Micic, V., Godec, R., Pavlović, M., Vastag, G. G., Ridosic, M., & Pavlović, M. M. (2016). Sage extracts as inhibitors of steel corrosion in 4% HCl. *International Journal of Electrochemical Science*, *11*(5), 3339-3350. [https://doi.org/10.1016/S1452-3981\(23\)17403-7](https://doi.org/10.1016/S1452-3981(23)17403-7)
- Torres-Ortiz, D., García-Alcocer, G., Loske, A. M., Fernández, F., Becerra-Becerra, E., Esparza, R., Gonzalez-Reyna, M., & Estevez, M. (2023). Green synthesis and antiproliferative activity of gold nanoparticles of a controlled size and shape obtained using shock wave extracts from *amphipterygium adstringens*. *Bioengineering*, *10*(4), 437. <https://doi.org/10.3390/bioengineering10040437>
- Untea, A., Criste, R., & Vladescu, L. (2012). Development and validation of a microwave digestion–FAAS procedure for Cu, Mn and Zn determination in liver. *Rev. Chim.*, *63*(4), 341–346. <https://doi.org/10.37358/Rev.Chim.1949>
- Valdez, N. A., Lopez-Sesenes, R., Larios-Gálvez, A., Vazquez-Velez, E., Uruchurtu-Chavarin, J., & Gonzalez-Rodriguez, J. (2022). Corrosion inhibition of aluminum 2024-T3 in 3.5% NaCl by using litchi chinensis extract. *Revista Mexicana De Ingeniería Química*, *21*(1), 1-15. <https://doi.org/10.24275/rmiq/Mat2504>
- Wang, Q., Tan, B., Bao, H., Xie, Y., Mou, Y., Li, P., Chen, D., Shi, Y., Li, X., & Yang, W. (2019). Evaluation of *Ficus tikoua* leaves extract as an eco-friendly corrosion inhibitor for carbon steel in HCl media. *Bioelectrochemistry*, *128*, 49–55. <https://doi.org/10.1016/j.bioelechem.2019.03.001>
- Xi, J., & Luo, S. (2016). The mechanism for enhancing extraction of ferulic acid from *Radix Angelica sinensis* by high hydrostatic pressure. *Separation and Purification Technology*, *165*, 208–213. <https://doi.org/10.1016/j.seppur.2016.04.011>
- Zakeri, A., Bahmani, E., & Aghdam, A. S. R. (2022). Plant extracts as sustainable and green corrosion inhibitors for protection of ferrous metals in corrosive media: A mini review. *Corrosion Communications*, *5*, 25–38. <https://doi.org/10.1016/j.corcom.2022.03.002>
- Zeković, Z., Pintač, D., Majkić, T., Vidović, S., Mimica-Dukić, N., Teslić, N., Versari, A., & Pavlič, B. (2017). Utilization of sage by-products as raw material for antioxidants recovery—Ultrasound versus microwave-assisted extraction. *Industrial Crops and Products*, *99*, 49–59. <https://doi.org/10.1016/j.indcrop.2017.01.028>