JURNAL KARTIKA KIMIA

J. Kartika Kimia, November 2025, 8, (2), 207-214
Journal homepage: http://jkk.unjani.ac.id/index.php/jkk
P-ISSN: 2655-1322 E-ISSN: 2655-0938

Enhancing Corrosion Resistance of AISI 1045 Carbon Steel Using *Rosmarinus officinalis* Extract: An Environmentally Friendly Approach

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DOI: https://doi.org/10.26874/jkk.v8i2.976

Received: 12 Aug 2025, *Revised*: 9 Dec 2025, *Accepted*: 10 Dec 2025, O*nline*: 23 Dec 2025

Abstract

Corrosion is the greatest challenge faced by various industries, especially those in maritime regions. This study evaluates the effectiveness of *Rosmarinus officinalis* extract as a corrosion inhibitor for carbon steel AISI 1045 in artificial seawater. Steel samples with varying inhibitor concentrations (0, 30, 60, 90, and 120 ppm) were immersed for 25 days. The results indicate that the weight gain due to corrosion for the sample without an inhibitor reached 79.5 mg, while the use of rosemary significantly reduced the weight gain, with the lowest corrosion rates recorded at 90 ppm (0.003 mpy) and 120 ppm (0.005 mpy). The optimal inhibitor efficiency was achieved at 60 ppm (75.57%). Microstructural analysis showed a decrease in pitting corrosion thickness and the formation of a new phase, Fe_3O_4, which is more stable and protective. These findings emphasize the potential of rosemary extract as an environmentally friendly solution for controlling corrosion in carbon steel, particularly in corrosive environments like seawater.

Keywords: Carbon steel, corrosion inhibitor, corrosion rate, pitting corrosion, *Rosmarinus officinalis*

1 Introduction

Corrosion, commonly referred to as rust, is a degradation process or a manifestation of damage to metals caused by environmental factors, including humidity, temperature, and the presence of certain chemical species [1]. Corrosion presents a significant challenge across various industries, particularly in marine and offshore applications [2]. AISI 1045 carbon steel, widely employed in structural applications due to its mechanical strength and cost-effectiveness [3], is highly susceptible to corrosion, especially when exposed to seawater [4]. Seawater contains chloride ions (Cl^-), which are the primary cause of corrosion in carbon steels [5]. Under such conditions, corrosion accelerates the deterioration of metals, thereby reducing the service life of infrastructure and significantly increasing maintenance costs.

To mitigate this problem, the use of corrosion inhibitors has become one of the most effective approaches to reducing corrosion rates [6]. Inhibitors form a passive film that impedes the interaction between aggressive ions and the metal surface, thereby slowing down electrochemical reaction rates [7]. Synthetic inhibitors, such as organic compounds and inorganic salts, are frequently used in industry [8]; however, many of these substances are toxic and environmentally unfriendly [9]. For example, chromate compounds have been banned in many countries due to their detrimental environmental impact. Therefore, selecting an appropriate inhibitor is essential to ensure effectiveness under various environmental conditions, particularly when prioritizing environmental sustainability [10].

With advancements in technology, research on corrosion inhibitors has evolved to focus on more efficient and environmentally friendly solutions. One innovative approach involves the use of organic, plant-based substances as inhibitors, which not only effectively suppress corrosion but also have minimal environmental impact. Previous studies have shown that natural compounds, such as plant extracts, can act as effective corrosion inhibitors, offering a sustainable alternative to synthetic chemicals that are often hazardous to ecosystems [11].

Rosmarinus officinalis (rosemary) essential extract has attracted considerable attention as a promising natural corrosion inhibitor. Rosemary extract contains bioactive compounds such as rosmarinic acid, caffeic acid, flavonoids, and terpenoids, which are known for their antioxidant and anti-inflammatory properties [12,13]. In corrosion control, antioxidants can inhibit oxidation reactions that trigger the onset of corrosion. Preliminary studies have demonstrated that rosemary extract can reduce corrosion rates in metals such as carbon steel and aluminum in both acidic and neutral media. However, in-depth investigations into its effectiveness as a corrosion inhibitor for AISI 1045 carbon steel (particularly in artificial seawater with a salinity of 35 g/L) remain limited.

Given this research gap, the present study aims to evaluate the effectiveness of *Rosmarinus officinalis* extract as a corrosion inhibitor for AISI 1045 carbon steel in artificial seawater. The methodology includes electrochemical techniques, such as potentiodynamic polarization, to determine corrosion rates and elucidate the inhibition mechanism of rosemary extract. The findings of this work are expected to contribute to the development of environmentally friendly corrosion inhibitors and to advance sustainable corrosion control technologies.

2 Method

This study utilized AISI 1045 carbon steel as the primary material, supplied by PT. Bohler Steel, Indonesia, with a carbon content ranging from approximately 0.45–0.55%. Rosemary essential extract (5 mL, 100% purity) from Bliss Scents, Indonesia, was used as the corrosion inhibitor. The inhibitor was applied at various concentrations of 0, 30, 60, 90, and 120 ppm. The corrosive medium was a 3.5 wt.% NaCl solution (35 g/L), prepared by dissolving analytical-grade sodium chloride (NaCl) in distilled water at room temperature to simulate a marine environment.

The chemical composition of AISI 1045 carbon steel was determined using optical emission spectroscopy (OES). Prior to measurement, the instrument was calibrated using certified reference materials (CRM) for carbon steel to ensure accuracy. The analysis was performed according to standard spark emission procedures for bulk steel composition determination, a Gamry Instruments Interface potentiostat/galvanostat for corrosion rate measurement, and an OHAUS Pioneer PA224 analytical balance for sample mass determination. Surface morphology was analyzed using a JEOL JSM-6510LV scanning electron microscope (SEM), while phase identification was performed using a PANalytical X'Pert Pro X-ray diffractometer (XRD).

AISI 1045 carbon steel samples were cut into discs measuring 20 mm in diameter and 5 mm in thickness, then sequentially ground with abrasive papers from grit 240 to 1200 to achieve a smooth surface. The specimens were cleaned with ethanol, rinsed with distilled water, and dried prior to testing.

The samples were immersed in the corrosive medium with varying inhibitor concentrations for 25 days at room temperature. Corrosion rates were determined from mass loss measurements before and after immersion. Further characterization was carried out using SEM and XRD to analyze surface morphology and identify corrosion products formed, as well as to evaluate the interaction between the inhibitor and the steel surface.

3 Result and Discussion

3.1. Chemical Composition Analysis of AISI 1045 Samples

The chemical composition analysis of the AISI 1045 carbon steel sample revealed a carbon content of 0.502%, with other elements including manganese at 0.691%, silicon at 0.246%, and phosphorus at 0.017% (**Table 1**). According to the Bohler High Grade Steels standard, the ideal carbon content for AISI 1045 carbon steel ranges from 0.40% to 0.50%. Therefore, the carbon content in this sample is slightly above the recommended upper limit, at 0.502%.

Table 1. Spectroscopic results of the chemical composition of low-carbon AISI 1045 steel.

	%C	%Si	%Mn	%P	%Cr	%Ni
AISI 1045	0.502	0.245	0.691	0.017	0.371	0.009
	%Al	%Cu	%Ti	%Fe	Ceq	
	0.009	0.032	0.003	98.113	0.695	

Carbon content plays a critical role in determining the corrosion characteristics of carbon steel, particularly its resistance to corrosion in aggressive environments such as seawater. Excess carbon can promote the formation of non-uniform carbides, which may serve as initiation sites for corrosion. The manganese content, measured at 0.691%, contributes to enhancing the steel's strength and hardness while improving wear resistance. Silicon in carbon steel functions as a deoxidizer, aiding in the removal of excess oxygen during the smelting process and thereby improving steel purity [14]. The silicon content in this sample (0.246%) falls within the expected range for AISI 1045, which is 0.15–0.35%. Although phosphorus is present in a very small amount (0.017%), excessive phosphorus can negatively impact steel toughness [15]. However, in this sample, phosphorus remains within acceptable limits, as AISI 1045 generally restricts phosphorus content to below 0.040%. Low phosphorus levels help maintain the steel's ductility, which is important for structural applications [16–18].

Overall, despite a slight deviation in carbon content from the recommended standard, the remaining chemical composition falls within acceptable ranges for AISI 1045 carbon steel, making it suitable for this study.

3.2. Effect of Inhibitor Concentration on Corrosion Rate and Inhibitor Efficiency

Mass measurement results indicated that as immersion time increased, the weight of the AISI 1045 carbon steel samples increased due to the formation of corrosion products (**Fig. 1**).

For samples without inhibitor addition (0 ppm), a significant mass gain was observed, increasing from 0.2 mg on the first day to 79.5 mg after 25 days. This mass gain indicates extensive formation of corrosion products on the steel surface, reflecting severe corrosion under uninhibited conditions. In the absence of inhibitor protection [19], carbon steel reacted aggressively with corrosive ions in artificial seawater [20].

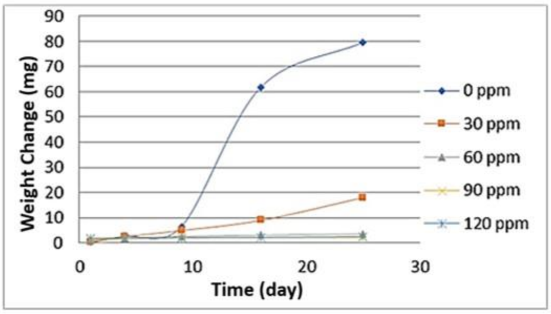


Figure 1. Variation in sample weight over Time

Conversely, when *Rosmarinus officinalis* extract was added at varying concentrations (30, 60, 90, and 120 ppm), the weight gain due to corrosion decreased significantly. At 30 ppm, the weight gain after 25 days was only 18 mg, suggesting that the inhibitor began to exhibit a protective effect, although not yet optimal. At higher concentrations, such as 60 ppm, 90 ppm, and 120 ppm, the weight gains were further reduced to 3.5 mg, 2.1 mg, and 2.3 mg, respectively, after 25 days. At 90 ppm and 120 ppm, the initial weight gain was minimal (1.4 mg and 1.6 mg, respectively) and remained very low after 25 days (2.1 mg and 2.3 mg, respectively). These findings indicate that rosemary extract effectively suppresses corrosion, particularly at higher concentrations, likely due to the formation of a robust protective layer on the steel surface that limits interaction between the metal and aggressive ions in the corrosive medium [21].

The corrosion rate for samples without inhibitor was significantly higher; however, increasing concentrations of rosemary extract led to substantial reductions in corrosion rate [22]. The lowest corrosion rate was observed at 90 ppm (0.003 mpy), followed by 120 ppm (0.005 mpy) (see **Fig. 2**). This suggests that while corrosion rate still decreased at 120 ppm, inhibitor efficiency did not improve beyond 90 ppm. This plateau effect may result from the formation of an optimal protective film at a certain concentration, with further increases providing no additional benefit and potentially decreasing inhibition efficiency [23].

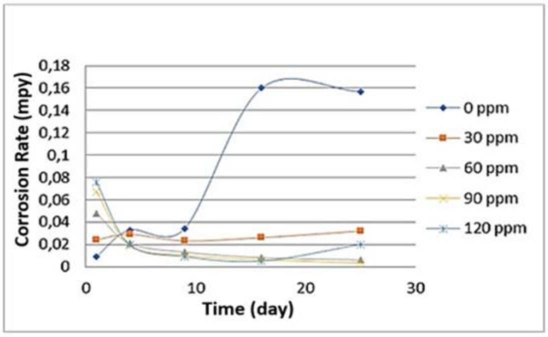


Figure 2. Corrosion rate of AISI 1045 carbon steel samples over immersion time

Based on gravimetric measurements, the inhibition efficiency increased with increasing inhibitor concentration up to 60 ppm, reaching a maximum value of 75.57%, as calculated from the reduction in mass gain relative to the uninhibited sample (see **Fig. 3**). At higher concentrations (90 ppm and 120 ppm), the efficiency decreased to 73.28% and 66.92%, respectively, possibly due to excessive adsorption of active molecules on the metal surface, which could disrupt the homogeneity of the protective film [24]. The inhibition efficiency (IE, %) was calculated based on gravimetric measurements using the mass change approach, according to **Eq. 1**.

IE (%) = $[(\Delta m_0 - \Delta m_i) / \Delta m_0] \times 100$ (**Equation 1**)

where Δm_0 is the mass gain of the sample without inhibitor and Δm_i is the mass gain of the sample with inhibitor after the same immersion time.

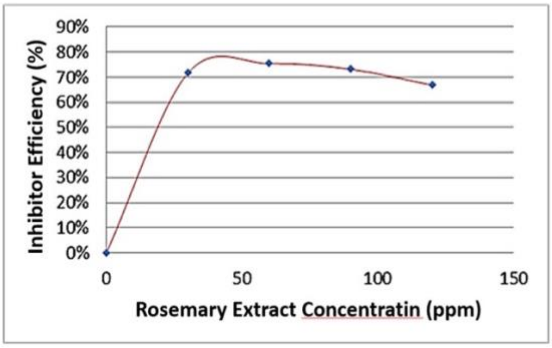


Figure 3. Efficiency of Rosemary Extract as a Corrosion Inhibitor

Overall, *Rosmarinus officinalis* extract proved effective in reducing the corrosion rate of AISI 1045 carbon steel in artificial seawater, with optimal performance observed at concentrations between 60 and 90 ppm.

3.3. Microstructural Analysis and Formation of Corrosion Products

Microstructural examination was conducted to observe morphological changes and phases formed on the AISI 1045 carbon steel surface after immersion for four days in corrosive media, with and without the addition of *Rosmarinus officinalis* extract (**Fig. 4**).

In samples without inhibitor (0 ppm), ferrite was the dominant phase, along with the formation of ferric oxyhydroxide (FeO(OH)) as the main corrosion product. In contrast, samples with 120 ppm inhibitor also exhibited magnetite (Fe_3O_4), which provides better corrosion protection.

These results indicate that rosemary extract reduces corrosion rates by forming a more stable protective layer, thereby improving the metal's corrosion resistance.

Figure 4. Macrostructure of the Top Surface of AISI 1045 Carbon Steel in 35 g/L NaCl Solution

3.4. Effect of Inhibitor on Pitting Corrosion Depth

The addition of rosemary extract significantly reduced pitting corrosion depth in AISI 1045 carbon steel (**Fig. 5**). Samples without inhibitor exhibited a pitting depth of 0.05 µm after four days of immersion due to the aggressive nature of chloride ions in artificial seawater.

Increasing inhibitor concentration resulted in decreased pitting depth. At 60 ppm, the depth was reduced to 0.0187 µm, highlighting the inhibitor's effectiveness in forming a protective layer that limits chloride ion penetration. On average, rosemary extract produced a pitting depth of approximately 0.02 µm, much lower than that of uninhibited samples [25].

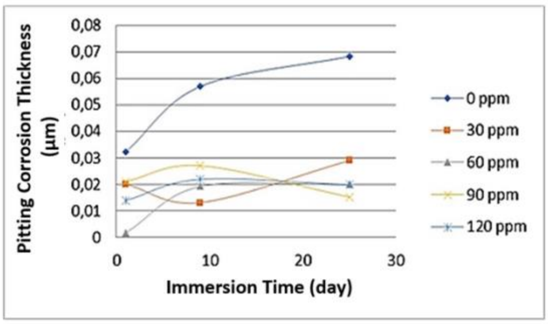


Figure 5. Pitting Corrosion Depth of AISI 1045 Carbon Steel Samples over Immersion Time

Interestingly, although 120 ppm remained effective in reducing corrosion rate, the pitting depth stayed at around 0.02 µm, indicating that concentrations above 60 ppm provided no significant additional protection, possibly due to excessive adsorption that reduced the homogeneity of the protective layer [26].

3.5. X-ray Diffraction (XRD) Analysis

XRD analysis revealed that before immersion, AISI 1045 carbon steel was dominated by α-Fe and Fe_3C phases (**Fig. 6**). Some diffraction peaks previously assigned to FeO were re-examined and are more likely associated with iron oxyhydroxide phases (FeOOH), due to peak overlap and the thermodynamic instability of FeO under aqueous corrosion conditions at room temperature (**Fig. 7**).

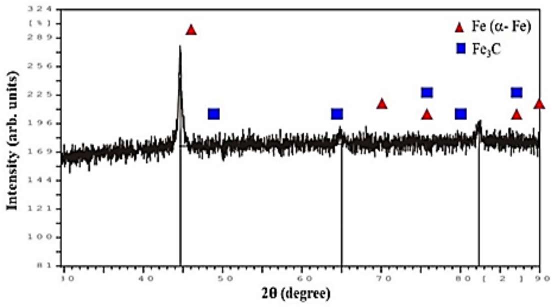


Figure 6. XRD analysis results of AISI 1045 carbon steel samples before immersion

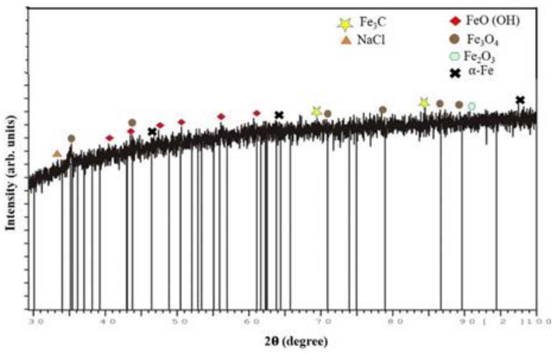


Figure 7. XRD analysis results of AISI 1045 carbon steel samples after immersion

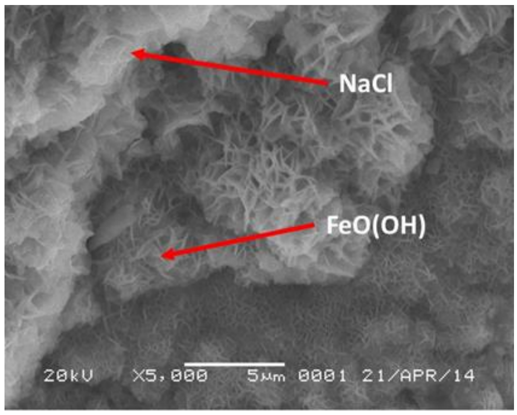
FeO is an initial corrosion product that lacks protective properties, whereas Fe_3O_4 is more stable and can form a passive layer that inhibits corrosion [27]. The presence of sodium chloride (NaCl) on the steel surface suggests that chloride ions from the corrosive solution contributed to pitting corrosion [28]. The addition of rosemary inhibitor suppressed FeO formation while promoting the formation of the more protective Fe_3O_4 phase, consistent with the pitting depth measurements [29].

3.6. Scanning Electron Microscopy (SEM) Analysis

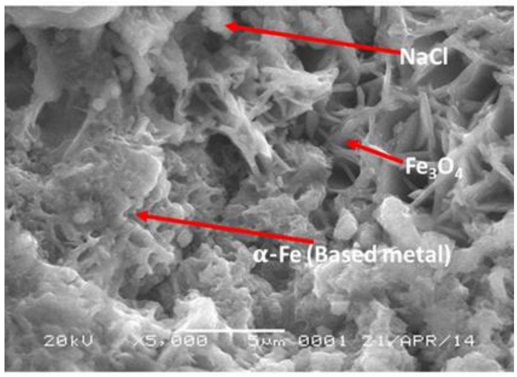
SEM observations of samples with 60 ppm rosemary inhibitor revealed the formation of an Fe_3O_4 layer on the steel surface (**Fig. 8**). This layer acts as a barrier, reducing the diffusion of corrosive ions and slowing the corrosion process [30].

Rosemary extract, which is rich in phenolic and antioxidant compounds, contributes to the formation of this protective layer. The microstructure reveals that the Fe_3O_4 layer is more homogeneous compared to other corrosion products, indicating the inhibitor's effectiveness in maintaining the integrity of the steel surface [31–32].

Thus, rosemary extract has strong potential as an environmentally friendly corrosion inhibitor for effectively protecting AISI 1045 carbon steel from pitting corrosion in artificial seawater.



(a)



(b)

Figure 8. SEM analysis of AISI 1045: (a) without rosemary inhibitor, and (b) with 60 ppm rosemary inhibitor

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4 Conclusion

This study demonstrates that *Rosmarinus officinalis* extract is effective as a corrosion inhibitor for AISI 1045 carbon steel in artificial seawater. The use of rosemary extract significantly reduced the corrosion rate, particularly at concentrations of 90 ppm and 120 ppm, with the lowest rate recorded at 0.003 mpy. The inhibitor efficiency peaked at 60 ppm, reaching 75.57%, although it slightly decreased at higher concentrations. Microstructural and SEM analyses revealed the formation of a protective Fe_3O_4 layer, which contributed to reducing pitting corrosion depth. Overall, rosemary extract has proven to be an effective and environmentally friendly solution for protecting steel against corrosion in marine environments..

Acknowledgement

The authors would like to express their gratitude to the Metallurgical Engineering and Mechanical Engineering Study Programs at Universitas Jenderal Achmad Yani, as well as BRIN Bandung, for their support in carrying out this research.

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