Efficiency of *Syzygium cumini* Fruit Extract as a Green Corrosion Inhibitor for Low Carbon Steel in Hydrochloric Acid Solution

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Abstract: *Organic plants are gaining serious attention as metal corrosion protection. As a non-toxic material,* Syzygium cumini *(SC) fruit extract contains antioxidant substances that can slow the corrosion rate. This research aimed to explore SC fruit extract as a green inhibitor of corrosion on AISI 1020 low carbon steel against exposure to 1 M HCl solution. SC fruit was extracted by the Soxhlet method and characterized using total flavonoids and tannins content. The inhibition systematics were analyzed using weight loss (WL), potentiodynamic polarization (PDP), and electrochemical impedance spectroscopy (EIS) methods. The results showed that the concentration of 600 mg/L had good corrosion inhibition effectiveness with efficiency reaching 72.91 (WL), 90.26 (PDP), and 75.15% (EIS). Surface characterization was investigated using scanning electron microscopy (SEM), Fourier transform infrared (FTIR), atomic force microscope (AFM), and X-ray diffraction (XRD) analyses. After the presence of inhibitors, corrosion products and damage to the steel were minimized compared to unprotected. This was based on the activity of inhibitor reaction to form a protective film. With the implementation of this material, SC fruit extract could be used as an environmentally friendly natural inhibitor.*

Keywords: *corrosion inhibitor;* Syzygium cumini *fruit extract; weight loss; potentiodynamic polarization; electrochemical impedance spectroscopy*

■ INTRODUCTION

Corrosion is a major obstacle to the weak resistance of steel to aggressive environments, such as in acidic media due to its continuous use [1-2]. Carbon steel, which is part of ferrous metals, is very susceptible to corrosion due to low potential energy [3]. However, carbon steel is still irreplaceable as the main material for construction with the advantages of malleability and good mechanical properties. Therefore, inhibition efforts are needed to prolong the life of steel and its usefulness. Economical and biodegradable corrosion control methods are the best option amidst the widespread use of synthetic materials, basically toxic in nature that can damage the environment and surrounding ecosystems [4].

Organic inhibitors obtained through plant extraction are reported to be ideal candidates for low-impact corrosion protection and becoming a leading research area every year [5]. Inhibitors mixed at low concentrations work efficiently by inhibiting the electrochemical reaction of metal with the environment thereby slowing down the degradation. Various factors such as pH, exposure time, and molecular shape of the inhibitor affect the percentage efficiency obtained. To produce excellent protective effects, the electronegative atoms (N, S, O, P) in natural compounds play a major role [6]. Additionally, hydroxyl, amine, and carbonyl functional groups play an important role in forming a coating layer. The mechanism of metal protection by inhibitor differs in each type of solution, showing the need for further research to produce the most suitable alternative. Achieving economical commercial requirements needs special attention to production costs and raw material availability.

According to previous research, organic inhibitors are adsorped and distributed from the solution, known as the dispersion process [7]. Organic materials developed contain complex compounds that can be dissolved or precipitated on the metal surface. The performance of organic inhibitor is observed based on the formation of a hydrophobic film layer which is influenced by several factors such as chemical structure, functional groups, and affinity [8]. Corrosion protection on metals through the affective inhibitor mechanism works based on the number of electrons released to the surface [9]. The inhibitor is adsorbed by forming a film, preventing metal from direct contamination with corrosive environment [10]. Research has increased significantly, suggesting that organic materials are good option for renewable, environmentally friendly protection methods [11].

Information related to the use of organic inhibitors has been widely published. Generally, natural materials used come from plant parts such as roots [12], stems [13], leaves [14], seeds [15], and fruit [16]. According to Ait Bouabdallah et al. [17], *Cleome arabica* L extract was used to protect carbon steel in 0.5 M HCl solution. Sajadi et al. [18] used *Lemon verbena* extract for mild steel (st37) in 0.5 M H_2SO_4 and 1 M HCl media. *Tabebuia heterophylla* plant leaf extract was also used for corrosion protection of low carbon steel in 1 M HCl medium by Pai et al. [19]. One of the plants with a strategic role as a corrosion inhibitor is *Syzygium cumini* (SC), which has been used as an organic inhibitor in HCl and H_2SO_4 solution [20]. In addition, the use of SC fruit has been carried out by Ali et al. [21]. SC fruit extract mixed with NaCl corrosive solution successfully reduced the rate of steel corrosion. This shows that SC fruit is among the best candidates as an organic inhibitor with numerous benefits. By maximizing the existing phytochemical content specifically, corrosion protection on metals requires high antioxidants such as tannins and flavonoids in the protection mechanism. This plant proves to have significant benefits in engineering.

In addition to the corrosive salt environment, acidic media have a fairly poor level of corrosiveness to metals [22-23]. In this recent research, SC fruit extract was used to inhibit the corrosion rate of low carbon steel exposed to an HCl solution. The extract was investigated as a green inhibitor through weight loss (WL), potentiodynamic polarization (PDP), and electrochemical impedance spectroscopy (EIS) methods. Therefore, this research aimed to analyze the performance of *SC* fruit extract inhibitors based on their effectiveness in protecting carbon steel. The phytochemical of the extract was analyzed by total flavonoids (TFC) and tannins (TTC) content. Metal surface characteristics of SC fruit extract on steel were determined by scanning electron microscopy (SEM), Fourier transform infrared (FTIR), atomic force microscope (AFM), and X-ray diffraction (XRD).

■ EXPERIMENTAL SECTION

Materials

The material used in this research was AISI 1020 low carbon steel. For WL testing, carbon steel was cut to a size of $3 \times 2 \times 0.3$ cm^3. Meanwhile, the PDP and EIS test specimens have dimensions of $1 \times 1 \times 2$ cm^3 which are coated with polyester resin and connected with copper wire on an open surface of 1 cm^2 [24]. The surface of the specimen was cleaned with sandpaper with grit 600 to 1200 mesh.

Instrumentation

PDP and EIS electrochemical measurements were carried out using a Potentiostat device (Autolab) supported by the Nova 2.1 application. The characterization surface of the specimens was examined by SEM, FTIR, AFM, and XRD methods. SEM and FTIR analyses were conducted using JEOL JSM 6510 LA device and Shimadzu IR Prestige-21 device, respectively. Meanwhile, AFM used a Bruker brand tool with the nanoscan type to determine the topography and calculate the roughness value on the sample surface and

XRD analysis was carried out using a test device with the Rigaku Miniflex 600 type.

Procedure

Preparation of SC fruit extraction and corrosive solution

The scheme for making SC fruit extract is shown in Fig. 1. Initially, 5 kg of SC fruit was collected from a farm in Aceh Besar, Indonesia, cleaned, and dried at 50 °C to remove water content. After drying, the SC fruit was crushed until smooth, followed by packing 250 g and placing into a Soxhlet tube. The extraction process used 1 L of 96% ethanol with three refluxes at 70 °C for 150 min. The extract was separated from the solvent using a rotary evaporator at 60 °C. This process produced pure *SC* fruit extract, packaged in bottles and stored at room temperature. The corrosive solution used was 37% HCl, diluted by mixing 83 mL of pure HCl into 1 L of of aquadest solution. *SC* fruit extract was mixed into the corrosive solution with concentration variations of 200, 300, 400, 500, and 600 mg/L.

Characteristics of SC fruit extract

TFC testing refers to the procedure carried out by Mwamatope et al. [25] using a standard quercetin solution. Meanwhile, the TTC test uses a standard tannic acid solution. The absorbance was calculated using a UV-vis spectrophotometer at 440 nm.

WL measurement

Carbon steel test specimens were prepared based on ASTM G1-03 standards [26]. Subsequently, carbon steel was exposed to 1 M HCl corrosive media without and with SC fruit extract inhibitor. This was followed by mixing inhibitor at various concentrations into the solution and stirring until homogeneous. Before testing, the specimens were cleaned to remove the oxide layer formed on the surface and weighed for initial weight. The specimens were exposed for 720 h, cleaned, dried, and reweighed at 5-day intervals as the final weight. Corrosion rate and inhibitor efficiency (IE) were determined using the Eq. (1) and (2) [27]:

$$\mathrm{Cr}\ (\mathrm{mm/y}) = \frac{\mathrm{K} \times \Delta \mathrm{W}}{\mathrm{A} \times \mathrm{T} \times \rho} \tag{1}$$

$$\mathrm{IE}\ (\%) = \frac{\mathrm{Cr}_0 - \mathrm{Cr}_{\mathrm{inh}}}{\mathrm{Cr}_0} \times 100\% \tag{2}$$

where Cr is the corrosion rate, K is the corrosion rate constant of 8.76×10^4 (mm/y), ΔW is the difference between the initial WL and the final weight of the specimen (g), A describes the surface area of the specimen 14.75 cm^2, T is the exposure time of the specimen to the solution (h), and ρ is the density of carbon steel at 7.85 g/cm^3. Meanwhile, Cr_0 and Cr_{inh} show corrosion rates without and with a mixture of inhibitors. For the characterization of carbon steel, specimens were immersed for 5 d in a 1 M HCl solution

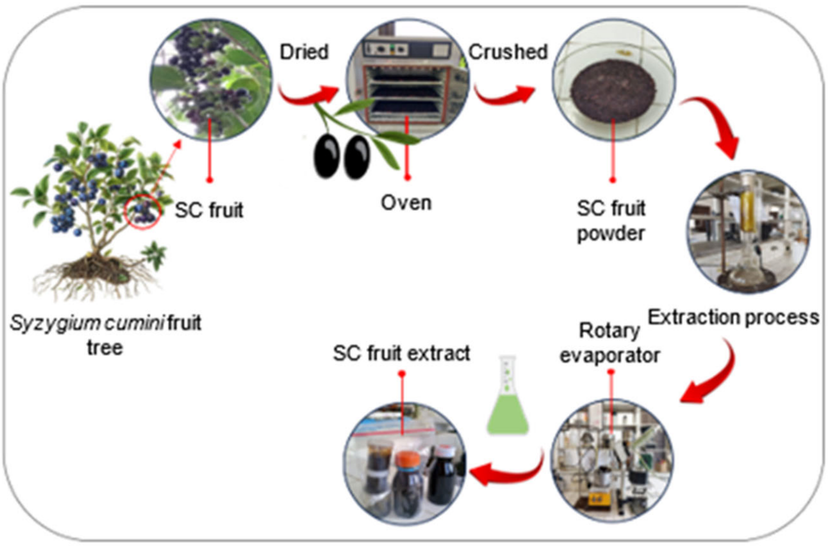

Fig 1. SC fruit extraction process

without and with a mixture of SC fruit inhibitor at an optimum concentration of 600 mg/L.

Electrochemical measurement

PDP and EIS method tests use three electrodes, namely the reference electrode (Ag/AgCl), the counter electrode (graphite), and the working electrode (carbon steel). PDP was carried out with a scan rate of 1 mV/s to produce a polarization curve with an electrode potential ranging from −200 to 200 mV. EIS testing was performed using an AC signal at an amplitude of 10 mV and a frequency ranging from 100 kHz to 10 mHz. Carbon steel specimens were immersed for 30 min before testing to be in a steady state. The inhibitor efficiency in PDP and EIS tests was calculated using Eq. (3) and (4) [28];

$$IE(\%) = \frac{i^0_{corr} - i_{corr}}{i^0_{corr}} \times 100\% \quad (3)$$

where i^0_{corr} and i_{corr} are corrosion current densities without and with a mixture of inhibitor. The i_{corr} values are obtained based Tafel extrapolation in the anodic and cathodic regions [29];

$$IE\ (\%) = \frac{R^0_p - R_p}{R^0_p} \times 100\% \quad (4)$$

where R^0_p and R_p are corrosion charge transfer resistance without and with the presence of an inhibitor. EIS curve fitting obtained the value of R_p which is useful for determining the efficiency.

■ RESULTS AND DISCUSSION

TFC and TTC Content

The antioxidant compounds of SC fruit extract in the form of flavonoids and tannins were investigated as important targets for active inhibitor ingredients on metals. The presence of these compounds was reported to support the performance of inhibitor in their movement to protect metals from corrosion attacks [30]. The results showed that SC fruit extract contained flavonoids of 2.11×10^7 mg/L, serving as a bioactive inhibitory ingredient on metals. Meanwhile, the level of tannins was shown to be 2.683×10^8 mg/L. These results showed that the content of tannins in SC fruit extract was more dominant than flavonoids. Tannins which are classified as polyphenols in plants play an important role in overcoming free radical attacks from the environment. The presence of these compounds showed that SC fruit extract could be used as a natural corrosion inhibitor [31]. The dependence on antioxidants as corrosion protection makes plants one of the best candidates as green inhibitor and solutions for the use of toxic materials.

WL Measurement

The inhibition of carbon steel corrosion rate by SC fruit extract inhibitor in 1 M HCl solution was carried out using the WL method. Corrosion rate was obtained based on the WL from the weighing results before and after immersion. The effect of exposure time was carried out with real practice, by showing its behavior during the exposure process and periodic weighing periods. Based on the research, the trend of corrosion rate decreased significantly at certain times along with increasing inhibitor concentration [32]. This behavior suggested that the immersion carried out allowed the reaction of iron ions in the metal to interact with inhibitor molecules, thereby forming a coating film.

The effect of immersion time determines the resistance of carbon steel to corrosion attack, affecting inhibitor effectiveness, stability, and adsorption process. The results show that, as the soaking time increases, inhibitor molecule interaction is improving. This suggests that the inhibitor can last and be durable over a long service life [33]. Initially, the inhibitor adheres to the surface in limited or suboptimal amounts. As time increases, the film formed becomes more stable and the molecules adhere perfectly over the period. Based on the test, the highest corrosion rate was 14.7 mm/y in the unprotected steel with an immersion time of 120 h (Fig. 2(a)). Increasing the exposure time caused a decrease in the corrosion rate and the lowest at the optimum concentration was 2.74 mm/y. At immersion times of 240 and 360 h, the inhibitor performance has not reached its stability which affects the acquisition of inhibition efficiency. However, increasing exposure time caused a rise in steel efficiency [34]. This behavior was caused by the movement of inhibitor molecules on the steel surface to prevent the formation of an oxide layer.

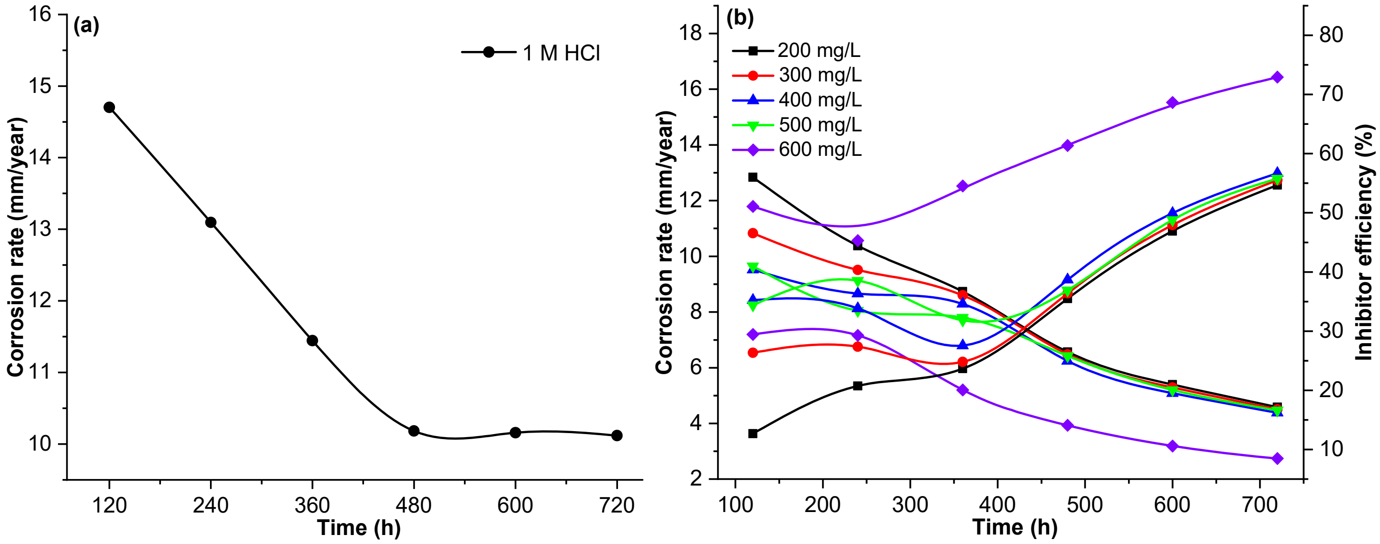

Fig 2. (a) Corrosion rate of carbon steel in 1 M HCl solution and (b) comparison of corrosion rate with SC fruit extract inhibitor efficiency based on immersion time

The maximum time duration indicates the formation of an optimal and cohesive protective layer.

The concentration level is an indicator of inhibitor behavior towards steel protection. This was evaluated by maintaining the soak time of 720 h at 25 °C. The amount of inhibitor concentration correlated with the efficiency obtained. When the inhibitor level of SC fruit extract was increased, the performance was better with high efficiency. The highest efficiency reached 72.91% at a concentration of 600 mg/L with an exposure time of 720 h (Fig. 2(b)). The addition of sufficient concentration, the inhibitors work perfectly, closing the possibility of direct exposure to an aggressive environment [35].

PDP Measurement

PDP measurement aims to further research the effect of adding SC fruit extract inhibitor in 1 M HCl solution on the corrosion rate of carbon steel. The test produces a polarization curve (Fig. 3) with measurement parameters in the form of corrosion potential (E_{corr}), corrosion current (i_{corr}), and polarization resistance (R_p). The intensity of the corrosion rate of carbon steel can be determined based on the test parameters produced (Table 1). The effective inhibitor was found to suppress corrosion rate by slowing down the anodic and cathodic reactions by increasing its activation energy, blocking the anode reaction, forming a passive layer, and limiting interactions in the reducing area.

Analysis in Table 1 shows that increasing the concentration of inhibitor in the solution successfully reduces the anodic and cathodic i_{corr} values [36]. The change in i_{corr} value is significant, starting from 0.0030 µA in 1 M HCl solution to the lowest at 600 mg/L of 0.0003 µA. This behavior has a direct effect on corrosivity of steel in aggressive environments. Corrosion rate is observed to be very high in the absence of an inhibitor and minimal when any current density decreases due to

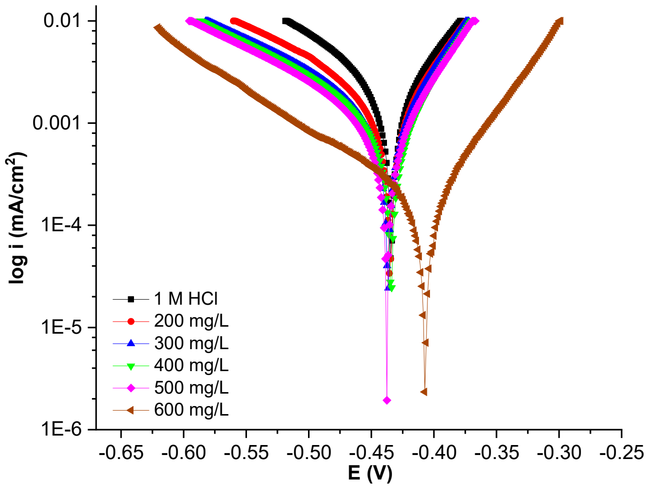

Fig 3. Polarization curves of carbon steel in 1 M HCl solution with and without SC fruit extract inhibitor

Table 1. Corrosion parameters of AISI 1020 steel calculated from polarization curves

Concentration (mg/L)	E_{corr} (V)	i_{corr} (μA)	R_p (Ω)	Cr (mm/y)	%IE
1 M HCl	−0.4351	0.0030	8.605	35.23	0
200	−0.4352	0.0020	12.727	23.82	32.39
300	−0.4377	0.0017	15.576	19.46	44.76
400	−0.4348	0.0014	18.874	16.06	54.41
500	−0.4384	0.0013	20.553	14.75	58.13
600	−0.4078	0.0003	88.494	3.43	90.26

the addition of inhibitor. The decrease in i_{corr} values is related to the adsorption of inhibitor compounds on the carbon steel surface blocking the accessibility of Cl^- ions from corrosive solution. However, E_{corr} relatively experienced a change that was in the negative direction. This proves that inhibitor dominantly inhibits corrosion in the reduction reaction [37]. According to the provisions in PDP measurement system, the shift of E_{corr} is less than 85 mV, emphasizing that SC fruit is a mixed-type inhibitor controlling the anode and cathode regions [38].

As shown in Table 1, the addition of an inhibitor to the solution affects the resulting measurement parameters. Increasing the concentration of inhibitor decreases the i_{corr} value and corrosion rate, thereby producing high-efficiency [39]. The calculation caused the highest efficiency of 90.26% at a concentration of 600 mg/L. The results of the observations showed that the adsorption process of SC fruit compounds was better as the concentration given increased. Therefore, the coverage on the surface was higher and the film layer formed was thicker starting from a concentration of 200 to 600 mg/L. The low corrosion rate and high inhibitor efficiency values can cause minimal damage and prolong the life of the steel. This gives SC fruit extract the potential for its contribution as a sustainable green inhibitor. Specifically, SC can be used in aggressive HCl solutions which are generally highly corrosive.

EIS Analysis

Fig. 4(a) shows Nyquist plots indicating the behavior of carbon steel in 1 M HCl solution without and with SC fruit extract inhibitor mixture. Nyquist plot shows the presence of a single capacitive loop, suggesting that steel corrosion control can be performed by a single charge transfer mechanism [40]. Moreover, the capacitive loop diameter is significantly affected by the inhibitor concentration. A higher diameter indicates that a larger concentration mixture correlates with an improved inhibitory effect on carbon steel [41].

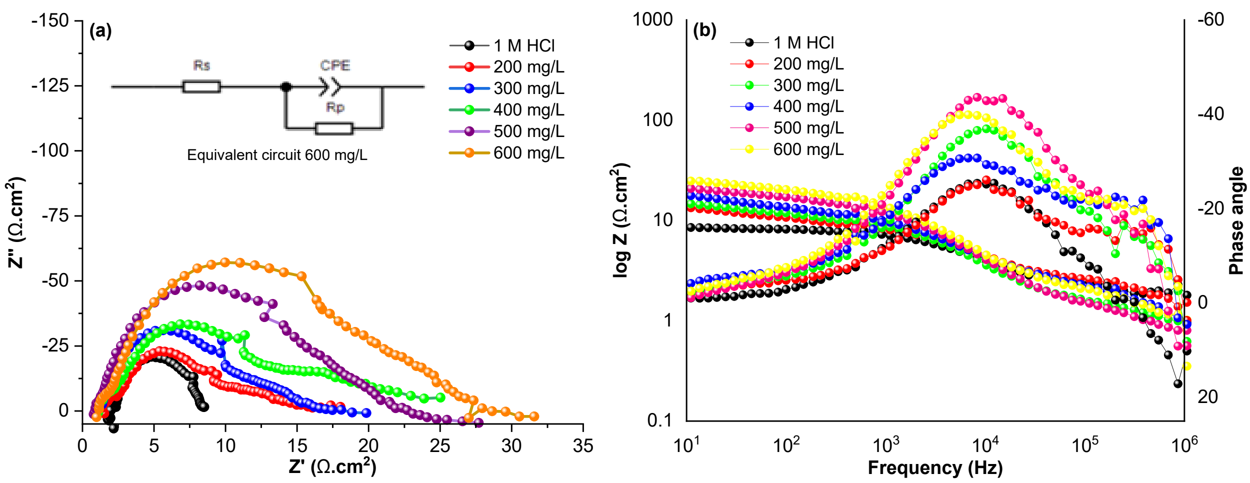

Fig 4. (a) Nyquist graph, (b) bode plot, and phase angle of carbon steel in a 1 M HCl solution with and without SC fruit extract inhibitor

Table 2. EIS experimental data on carbon steel

Concentration (mg/L)	R_s (Ω/cm^2)	R_p (Ω/cm^2)	CPE-T (μF/cm^{-2})	CPE-P (μF/cm^{-2})	E_{EIS}%
1 M HCl	2.08	6.16	$3.84.10^{-4}$	0.79	0
200	1.27	13.72	$4.73.10^{-3}$	0.45	55.10
300	0.97	14.22	$1.44.10^{-3}$	0.61	56.69
400	0.89	19.54	$3.58.10^{-3}$	0.47	68.47
500	0.86	20.36	$7.14.10^{-4}$	0.67	69.74
600	1.13	24.79	$9.46.10^{-4}$	0.62	75.15

The electrochemical parameters of the EIS test are generated based on an equivalent circuit, as shown in Fig. 4(a). The existing electrical circuit is used to determine the electrochemical behavior under investigation. This circuit consists of an intermetallic R_p, a constant phase element (CPE) to represent the electrical double layer between the steel surface and the solution. Another element is the solution resistance (R_s), which is connected in series with the constant phase element [42].

The electrochemical parameters of the EIS test were generated based on the equivalent circuit, as shown in Table 2. The analysis carried out showed that the addition of an inhibitor to corrosive solutions affected the R_p value. Furthermore, with increasing concentration mixed, the R_p value increased with a very striking difference compared to without an inhibitor [43]. The solution without inhibitor produced an R_p value of 6.16 Ω/cm^2. Meanwhile, with a mixture of the inhibitor, R_p values were obtained at 13.72, 14.22, 19.54, 20.36, and 24.79, respectively, producing better resistance to charge transfer. The increase in the R_p value and the optimum at a concentration of 600 mg/L showed that the inhibitor successfully inhibited the corrosion rate well. This value confirms that more inhibitor molecules are adsorbed and bound to the steel surface [44].

From the electrical circuit, the CPE is connected in parallel with R_p. When the inhibitor is added, there is a change in the value of the double layer of surface and solution. This behavior is due to the activity of the inhibitor to adsorb and form a thin film on the steel surface [18,45]. The change in CPE value shows that the dissolution of metal ions occurs more slowly to improve the corrosion resistance of steel [19]. The performance of the inhibitor can be further determined based on the percentage of efficiency. In this research, efficiency rose with increasing inhibitor concentrations. Efficiency obtained was 55.10, 56.69, 68.47, 69.74, and the maximum reached 75.15%. The high efficiency obtained proved that the SC fruit extract inhibitor provided a very good corrosion inhibition effect. The comparison of efficiency obtained in the 3 test methods, showed the suitable inhibition power and the SC fruit extract inhibitor was most preferred at the optimum quantity (600 mg/L). Further study using this method can be proven by the bode diagram in Fig. 4(b). Based on the results, the impedance value tends to increase along with the concentration of SC fruit extract. The phase angle also appears to be larger due to the protection of steel compared to the control.

SEM

SEM testing on carbon steel surfaces aims to detect the inhibitor performance. The topographic appearance of the steel surface was studied under different conditions, namely steel in a polished state (Fig. 5(a)), after immersion in 1 M HCl solution (Fig. 5(b)), and in corrosive solution mixed with 600 mg/L inhibitor concentration (Fig. 5(c)). As shown in Fig. 5, significant differences in steel were observed across various scenarios. Initially, the polished carbon steel shows a smooth and undamaged surface, with traces of liner-shaped lines. After the treatment, steel starts to degrade significantly following immersion in 1 M HCl solution. Subsequently, the surface becomes rough, leading to the formation of pitting corrosion due to chloride ions concentrated in certain parts. This is localized corrosion of the metal that leads to the formation of dangerous cavities. The pitting that forms can quickly damage the structure of the steel. In comparison, the surface condition is better after the steel is protected by the inhibitor due to the formation of

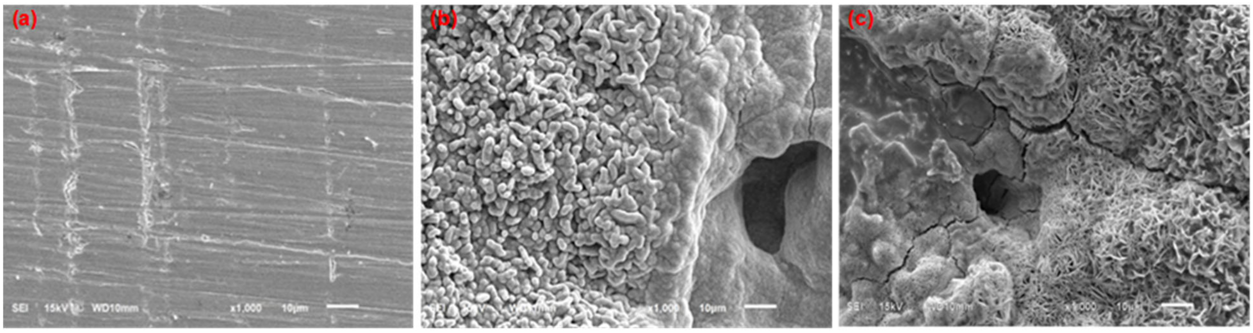

Fig 5. (a) SEM scans of polished steel, (b) in I M HCl solution, and (c) SC fruit extract inhibitor mixture

a protective film layer. The lack of damage is due to the movement of inhibitor molecules blocking the direct electrolytic process between the steel and the aggressive environment [14]. The addition of SC fruit extract inhibitor shows its role in reducing the corrosion rate and slowing down the steel degradation [46].

FTIR

The performance of SC fruit extract to protect steel from degradation is attributed to the adsorption process of inhibitor molecules on the surface. To support this statement, FTIR analysis was applied to pure SC fruit extract and carbon steel after inhibition, with the results shown in Fig. 6. The analysis showed that SC fruit extract produces functional groups playing an active role during the adsorption process. The functional groups associated with the process included hydroxyl (O−H), alkane (C−H), carbonyl (C=O), ether (C−O), and P−O stretching mode of PO_4^{3-}. Steel protected with SC fruit inhibitor produced similar functional groups and relatively lower intensity compared to the pure extract [47]. This intensity change occurred at the absorption peaks, 3360 to 3304, 2933 to 2900, 1724 to 1681, 1217 to 1182, and 1041 to 1012 cm^{-1}. The results showed that there was an interaction behavior between the inhibitor molecules on the steel surface. This suggested that there was a very good adsorption process by the electronegative inhibitor atoms on the steel surface in corrosive solution [48-49].

AFM

The surface topography of carbon steel after being soaked in a 1 M HCl solution and a mixture of 600 mg/L SC fruit extract inhibitor is shown in Fig. 7. The surface

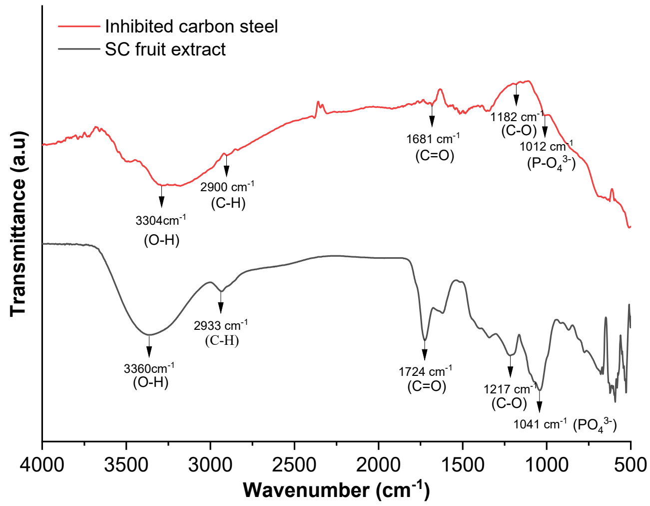

Fig 6. FTIR spectra of pure SC fruit extract and carbon steel with SC extract inhibitor

roughness in conditions without inhibitor appears significantly high and experiences major degradation. As a comparison, the presence of an inhibitor successfully reduces the surface roughness value and decreases substantially. AFM analysis data in the form of maximum roughness (R_{max}), average roughness (R_a), and root mean square roughness (R_q) are shown in Table 3.

The roughness statistics on carbon steel in Table 3 without inhibitor appear very high. The R_a value obtained was 48.7 nm, 61.9 nm on the surface of R_q, and R_{max} was 601 nm. The high surface roughness of steel is influenced by attacks from H^+ and Cl^- ions contained in the solution [50]. These results showed that direct contamination of carbon steel with corrosive solutions causes more severe damage. Furthermore, the surface was covered by many layers of oxide, which facilitated degradation (Fig. 7(a)). The opposite results were shown in Fig. 7(b), where the

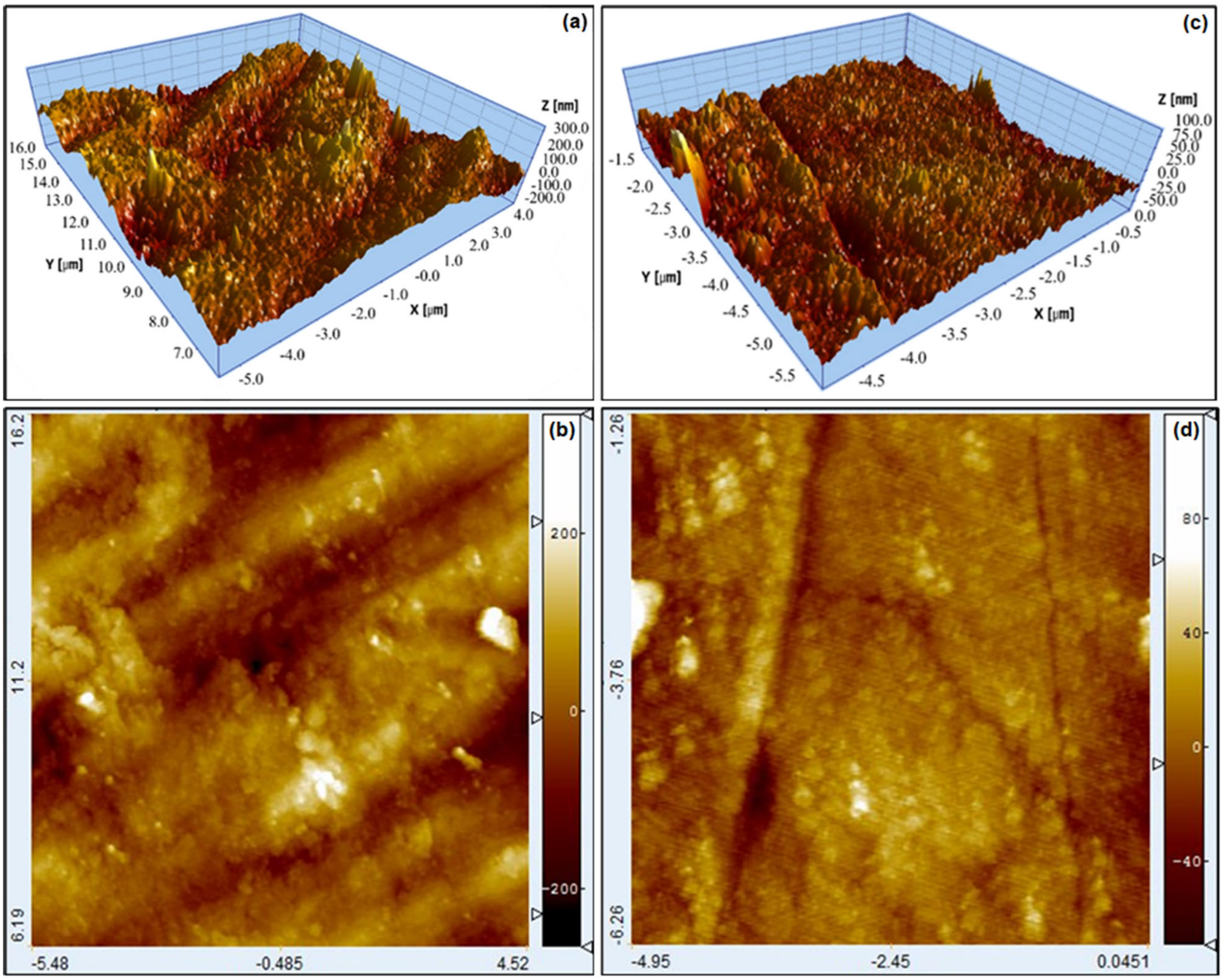

Fig 7. (a, b) AFM topography of carbon steel without and (c, d) with SC fruit inhibitor

Table 3. AFM parameters of carbon steel

Concentration	R_{max} (nm)	R_q (nm)	R_a (nm)
1 M HCl	601	61.9	48.7
600 mg/L	186	15.5	11.8

corrosion layer appeared thinner and experienced little degradation. The R_a value obtained was 11.8 nm, R_q was 15.5 nm, and R_{max} reached 186 nm. This incident was caused by the protection carried out by the SC fruit extract inhibitor on steel. The addition of extract (600 mg/L) to the solution caused the surface to appear smoother. The roughness decreased due to the formation of a protective layer by inhibitor, in line with the research by Kavitha et al. [51].

Corrosion products formed on the surface without inhibitor appeared more, as showed by towering topographic surface mounds. This was different from the surface with a protective layer, where fewer corrosion products were formed [52]. The results confirmed that the addition of SC fruit extract provided a very good corrosion inhibition effect. The reaction of compounds and functional groups of SC fruit extract allowed the inhibitor to be adsorbed more on the steel surface. This phytochemical substance formed a protective layer, slowing down the electrochemical reaction of corrosion from H^+ and Cl^- ions in solution. Anodic and cathodic reactions can be well controlled by

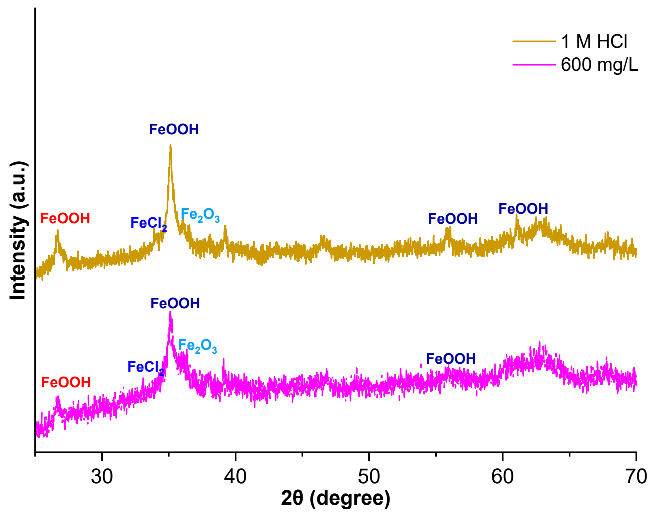

Fig 8. XRD pattern of carbon steel after being soaked in 1 M HCl and a mixture of 600 mg/L inhibitor

inhibitor, thereby extending the corrosion process.

XRD

XRD pattern and compounds formed on the surface are shown in Fig. 8. Based on the tests carried out, each condition produced several corrosion products with different intensities. The results showed that steel immersed in 1 M HCl solution had the highest peaks at 2θ of 65°. With this intensity, corrosion products formed were more dominant compared to the presence of an inhibitor. The high peak in the XRD pattern showed that the corrosion products formed were thicker, as also reported by Shahmirzadi and Azadi [53]. The most dominant compound formed was found to be FeOOH (goethite), which was an oxidant mineral in corrosion products [54]. At an angle of 48.27°, the formation of the $FeCl_2$ phase (lawrencite) was a corrosion product formed due to the reaction between Fe and Cl^- ions in a corrosive solution. Moreover, at an angle of 67.1°, a corrosion product was formed in the form of Fe_2O_3 (hematite). At low intensity with angle of 18.51°, the formation of the goethite phase was also shown [53,55]. This suggested that the steel surface was coated with many corrosion products, leading to damage in unprotected conditions.

Compared to materials protected by inhibitor, corrosion products on steel surfaces were formed with lower and thinner intensity. Based on the analysis results, at 2θ = 65°, goethite was less compared to steel without protection. Similar results were obtained at 2θ = 48.41°, where the corrosion phase was formed as lawrencite. At 2θ = 67.79°, a compound was formed on the surface in the form of Fe_2O_3 (hematite). Moreover, at an angle of 18.79°, the goethite formed was less than the previous results in unprotected conditions. The protection through the reaction of inhibitor on the steel surface caused the formation of minimal surface corrosion. The XRD pattern and corrosion products formed were relatively the same, although differences occurred in terms of intensity. This showed that adding inhibitor to corrosive solutions could reduce the rate of corrosion. Based on the results, the SC fruit extract inhibitor showed the potential to be adsorbed on the surface through the physisorption stage.

■ CONCLUSION

This research showed that SC fruit extract was suitable for use as a corrosion inhibitor for carbon steel in a 1 M HCl corrosive solution. The active inhibitor formed a protective film layer that tended to be effective as the concentration increased, specifically at 600 mg/L. Steel corrosion characterization identified that SC fruit extract behaved as a mixed-type inhibitor. Based on the tests conducted, the best efficiency of the inhibitor was obtained at 72.91% (WL), 90.26% (PDP), and 75.15% (EIS) in each method. Surface morphology analysis showed that inhibitor-protected steel experienced minimal degradation. There was a low intensity of corrosion products with inhibitor compared to when the unprotected steel. This research showed that SC fruit extract inhibitor contributed to the development of environmentally friendly steel corrosion protection.

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■ CONFLICT OF INTEREST

The authors have no relevant financial or nonfinancial interests to disclose.

AUTHOR CONTRIBUTIONS

Nurdin Ali as the compiler and designer of the experiment, Syarizal Fonna revised the manuscript, Yumaidi Saputra conducted the research and wrote the manuscript, Ahmad Kamal Ariffin and Joli Supardi contributed to materials, analytical tools or data. All author agreed to the final version of this manuscript.

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