

Development of an empirical model for predicting carbon steel corrosion rate using *Melastoma candidum* leaves extract an inhibitor

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Abstract. Giving significant attention to carbon steel corrosion is essential for predicting damage and loss and for determining appropriate protection methods. Several studies have shown that measuring corrosion rate based on weight loss is a simple method, but it is relatively time-consuming. Therefore, this study aims to develop an empirical model for the corrosion rate of carbon steel in a corrosive environment containing 3.5% NaCl, protected by an inhibitor derived from *Melastoma candidum* leaves. The 18 carbon steel plate samples were immersed in separate containers consisting of inhibitor concentrations of 0, 200, 400, 600, 800, and 1000 ppm, respectively, and in 3.5% NaCl for 30 days. The developed empirical model was based on the relationship between corrosion rate and inhibitor concentration at specific time intervals. The analysis showed that both the experimental testing and the developed empirical model produced valid results, as showed by a trend line graph. This empirical model provided a novel contribution to predicting corrosion protection for carbon steel. The highest corrosion rate obtained for unprotected steel specimens was 0.32 mm/year, and decreased significantly with increasing inhibitor concentration.

1 Introduction

Corrosion, also known as rust, is an undesirable process that can reduce the service life and aesthetics of materials. In addition, it is the process by which a metal returns to the original form of iron ore after interacting with the environment [1]. Several factors influence this process, but water media containing strong electrolytes, such as NaCl, exhibit unique

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properties. The electrolytes dissolve in water to form Na^+ and Cl^- ions, and the presence of Cl^- ions accelerates the electrochemical corrosion [2]. The emergence of corrosion causes metal degradation, with consequences for society, including losses, adverse environmental effects, and even death. Preventive efforts made using additives often worsen the problem. As a preventive measure against this problem, the development of natural materials is urgent, namely organic inhibitors derived from plant extracts [3].

According to previous studies, inhibitors effectively prevent metal corrosion by forming a barrier that stops corrosive substances from directly interacting with the surface [4]. Depending on the type of phytochemical and the amount of active ingredients, organic inhibitors derived from plant materials vary in effectiveness and inhibition mechanisms. This protection has been previously investigated, showing that plant extracts are widely used agents due to their environmentally friendly nature [5]. Metal corrosion inhibition is also influenced by several factors, such as variations in concentration, environmental pH levels, and room temperature. In addition, the type of corrosive solution influences how its ions and molecules bind to the metal surface.

The effectiveness of metal protection can be determined from the corrosion rate value, both with and without the presence of inhibitors. The corrosion rate value can be calculated as the difference between the initial and the final weight divided by time [6]. However, to improve the effectiveness of this method, a simpler, more accurate approach is needed. Several studies have reported the influence of using inhibitors to protect steel, such as those conducted by Ali Nurdin, et al (2024) and Nurdin Ali, et al (2025) [7][8]. Despite the existing literature, these studies have been limited to experimental testing, and no model has been applied empirically. Empirical modeling has only been used to predict the corrosion rate of steel in various applications, such as determining the rate of atmospheric corrosion and in acidic environments [9]. Therefore, this study aims to develop a previously developed empirical model to predict the corrosion rate of metals based on the relationship between exposure time and changes in inhibitor concentration. The model can predict the rate of metal corrosion protected by *Melastoma candidum* leaves extract inhibitors. The protection of steel against corrosion by inhibitors is predicted using the weight loss method. Then, the corrosion rate obtained is predicted using a model (power-law equation) to predict the accuracy of the experimental corrosion rate [10]. Thus, this research is novel in the topic of inhibitors, which has never been done before.

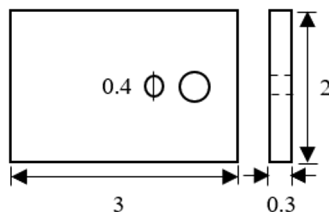
2 Materials and Method

2.1 Corrosive Materials and Solutions

This study used AISI 1020 carbon steel purchased from a hardware store in Banda Aceh, Indonesia. The composition of the carbon steel is presented in Table 1 [7]. The steel was prepared in pieces measuring 3 cm long, 2 cm wide, and 0.3 cm thick, with a 0.4 cm hole drilled in them, as shown in Figure 1. A total of 18 sheets of the same size were prepared for this purpose, then exposed to a corrosive solution and a mixture of inhibitors. Pure crystalline NaCl had been obtained from a store in CV. Rudang Jaya, Medan, Indonesia. A 3.5% NaCl solution functioned as the corrosive medium, prepared by diluting 35 g of crystalline NaCl into 1 L of distilled water.

Table 1. Chemical composition of AISI 1020 steel

C (%)	Si (%)	Mn (%)	P (%)	S (%)	Cr (%)	Mo (%)	Ni (%)	Cu (%)	Al (%)	Nb (%)	Fe (%)
0.18	0.26	1.25	0.03	0.03	0.15	0.03	0.09	0.28	0.01	0.01	Balance

**Fig 1.** Weight loss test specimen (in cm)

1.2 Experimental Procedure

The main ingredient for the inhibitor was extracted from *Melastoma candidum* leaves using the Soxhlet method. GC-MS results showed the presence of several dominant compounds, such as 5-Hydroxymethylfurfural, beta-D-Glucopyranoside, Hexadecanoic acid, methyl ester, 9, 12, 15-Octadecatrienoic acid, which plays an important role during the corrosion inhibition process in carbon steel [11]. In addition, the prepared corrosive solution (3.5% NaCl) was mixed with the inhibitor at concentrations of 0, 200, 400, 600, 800, and 1000 ppm. This process included stirring with a magnetic stirrer for 15 minutes until the solution became completely homogeneous. The cut carbon steel was then cleaned with sandpaper with a coarseness ranging from 180 to 800 mesh. This was carried out to smooth the surface and remove any existing metal corrosion.

The initial weight of the steel was determined by weighing and recorded as the initial weight. A total of 6 immersion containers were prepared, each containing 3 samples. The total sample set was divided into 6 groups under different conditions. In this study, the first group, consisting of 3 specimens, was exposed to an unprotected NaCl solution, while the remaining 5 groups, each also containing 3 specimens, were exposed to solutions containing additive concentrations of 200, 400, 600, 800, and 1000 ppm, each at room temperature (± 25 °C). Immersion lasted 30 days, with weighings every 3 days. This weighing served as a reference for the final weight of the samples, allowing for the calculation of the difference in steel weight before and after exposure.

1.3 Determination of Corrosion Rate and Modeling

A quantitative method was used to calculate the corrosion rate of each carbon steel after treatment. The cross-sectional area of the test specimen was measured accurately to observe the surface area exposed during the experiment. This surface area was determined using the following equation 1:

$$A = [2 \times (P \times L) + (P \times T) + (L + T)] - 2(\pi r^2) \quad (1)$$

Where A was the cross-sectional area of carbon steel (in cm²), P was the length of the carbon steel specimen (in cm), L was the area of the carbon steel specimen (in cm), T was the height of the carbon steel specimen (in cm), and r was the radius of the perforated part of

the specimen (in cm). The calculation of the corrosion rate of carbon steel was produced based on the following Equation 2:

$$Cr = \frac{8.76 \times 10^4 \times \Delta W}{A \times t \times \rho} \quad (2)$$

Where Cr was the corrosion rate of carbon steel at each concentration (mm/year), ΔW was the weight difference of the carbon steel specimen (g), A was the surface area produced according to equation 1 (cm²), t was the variation of the exposure time of the carbon steel, and ρ was the density of the carbon steel (g/cm³). The effectiveness of corrosion inhibitor inhibition could be determined using Equation 3:

$$EI = \frac{Cr_0 - Cr_{inh}}{Cr_0} \times 100\% \quad (3)$$

Where EI was the inhibitor efficiency (%), Cr_0 and Cr_{inh} were the corrosion rates with and without corrosion inhibitor protection (mm/year). Data from six steel treatments were used to develop an empirical model to predict corrosion rates at varying inhibitor concentrations. The empirical model that was developed was based on a power-law function, based on the following Equation 4:

$$Cr(t, C) = a(C) \times t^{b(C)} \quad (4)$$

Where Cr (t,c) was the carbon steel corrosion rate model (mm/year), a was the experimental constant obtained through initial regression, and b signified the constant derived from further regression. C was the variation in concentration mixed into the corrosive solution (ppm), and t was the exposure time of the carbon steel specimen (days).

3 Results and Discussion

1.4 3.1 Analysis of Corrosion Rate and Model Formulation

The influence of inhibitor concentration mixed in a 3.5% NaCl corrosive solution and immersion time was a major factor in this study. Weight loss in carbon steel showed the corrosion rate, which was calculated as the difference between the initial weight and the final weight after a specific exposure time.

The corrosion rate of carbon steel at each concentration was calculated based on equation 2, stating that increasing the concentration level given than the corrosion rate decreased significantly [12]. Moreover, the longer the exposure time, the better the corrosion resistance of carbon steel, which was shown by the low corrosion rate value [13]. The inhibitor concentration and immersion time were the main factors that determined the speed of the corrosion rate and resistance to corrosive environments containing Na⁺ and Cl⁻ ions.

An empirical model was applied to predict the corrosion rate of carbon steel at a given concentration and time unit [14]. Based on this study, this model verifies the experimental results. The curve plot in Figure 2 represented a data fitting between the corrosion rate of carbon steel versus immersion time (days). The curve fitting results showed that the best parameter relationship was observed based on the highest R² value of 0.99 (Table 2). Based on this graph, a model expressed based on a power-law through multilevel data regression was obtained, expressed in equation 4.

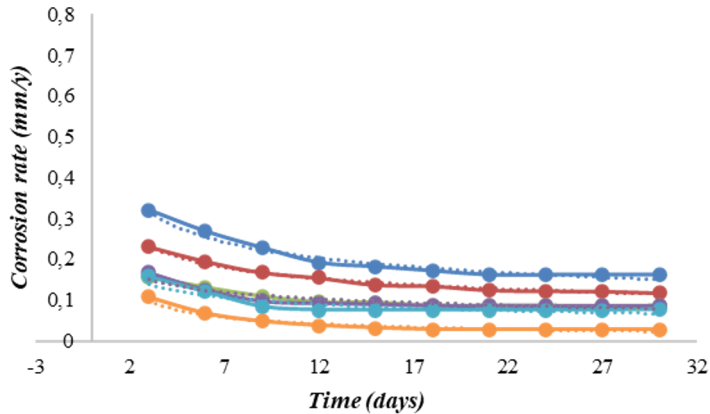


Fig 2. Plot the curve between corrosion rate (Cr) against time (t) at various concentrations

The decrease in the corrosion rate was caused by the formation of a thin film layer derived from the inhibitor of *Melastoma candidum* leaves extract. This protective layer is formed based on inhibitor molecules adsorbed on the surface of carbon steel. In addition, this process occurred well, which was limited by its effectiveness during immersion. The presence of the inhibitor limited the direct interaction between the steel and the corrosive environment, thereby inhibiting the electrochemical process of corrosion, which resulted in a lower corrosion rate [15]. This was also proven by the applied empirical model, namely the value of a decreases from 0.456 to 0.196 along with increasing inhibitor concentration, due to the presence of a protective layer by the corrosion inhibitor. By drawing a graph of the relationship between a and concentration (C) in Figure 3, a very strong relationship was obtained with the highest R^2 value of 0.97, resulting in an equation 5:

$$a = 0.451 - 0.0007 \times C + 4.90e^{-7} \times C^2 \quad (5)$$

Where C was the inhibitor concentration (ppm).

A further regression was performed between the n value in the initial regression and the inhibitor concentration to determine the b value. The regression results obtained the best R^2 value of 0.85, which yielded an equation of 6:

$$b = -0.359 + 0.0006 \times C - 8.48e^{-7} \times C^2 \quad (6)$$

Equation b also states that as the concentration increases, the value of b decreases. This result is similar to the value of a , which often decreases the rate of corrosion. Then, the substitution of equation (4) with (5) and (6) produced a new equation, which was used to determine the empirical model of the corrosion rate, as seen in equation 7:

$$CR(t,C) = [0.451 - 0.0007 \times C + 4.90e^{-7} \times C^2] \times t^{[-0.359 + 0.0006 \times C - 8.48e^{-7} \times C^2]} \quad (7)$$

To produce an empirical model of corrosion rate based on equation (7), variations in concentration and exposure time were important factors that must be considered.

Table 2. Parameter values of the equation $Cr(t,C) = a(C) \times t^{b(C)}$

Konsentrasi	a	n	R ²
NaCl 3,5%	0.456	-0.325	0.976
200 ppm	0.327	-0.306	0.992
400 ppm	0.206	-0.280	0.955
600 ppm	0.204	-0.275	0.890
800 ppm	0.196	-0.314	0.863
1000 ppm	0.196	-0.623	0.970

1.5 Model Validation

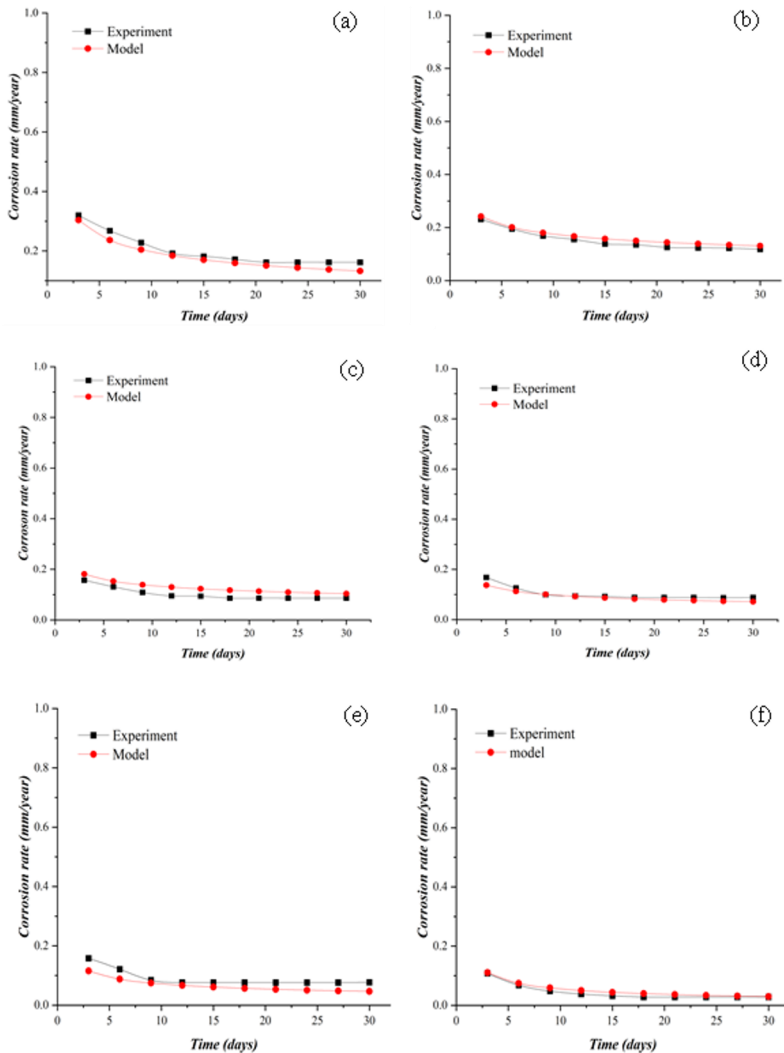


Fig 3. Plot of corrosion rate curve (Cr) against time (days) at concentrations of (a) 0, (b) 200, (c) 400, (d) 600, (e) 800, and (f) 1000 ppm

The obtained equation was proposed as a model to be applied in investigating experimental data obtained in the field. Therefore, this model must also be supplemented with data to ensure that this equation was correct and had a strong basis. The application of equation 5 allowed for the calculation of the corrosion rate based on variations in concentration and time, with data validation based on Figure 3 and supplemented with Table 3. This calculation produced corrosion rate values that were almost the same as the experimental data. The graphical representation of each inhibitor concentration showed a very good relationship with 2 straight lines that had a similar trend, and the proposed model also has a similar trend from both experimental data lines, so that the proposed model has good suitability.

The average error obtained at each concentration was 10.09% (0 ppm), 8.77% (200 ppm), 20.82% (400 ppm), 11.87% (600 ppm), 37.64% (800 ppm), and 16.04% (1000 ppm). In addition, the model applied as a whole could be accepted as the initial stage of modeling, specifically at concentrations of 0, 200, 600, and 1000 ppm, with an average error value below 15% and the best at a concentration of 200 ppm with an average error value of 8.77%. The decrease in the average error value, starting from 37.63 to 20.82 to 16.04 to 11.87 to 10.09 to 8.77% at concentrations of 800 to 400 to 1000 to 600 to 0 to 200 ppm, was caused by the influence of the inhibitor concentration, which prevented the metal surface from being attacked by corrosive compounds. However, at certain concentrations, the developed model showed poor accuracy, along with the desorption process of the inhibitor.

In this study, the immersion time determined the performance and effectiveness of the inhibitor's resistance in carrying out its role. The adsorption of inhibitor compounds from *Melastoma candidum* leaves that formed a thin film on the surface also determined the inhibition value of the inhibitor measured based on equation 3. In addition, the higher the inhibition value obtained, the better the inhibition, which caused minimal degradation of the metal. The model applied in this study could be used as a reference [10][14] during the validation process of experimental data through weight loss measurements. This was used to predict the corrosion rate inhibited by the inhibitor. The application of the proposed model is limited and depends on the concentration of the inhibitor (C). The conclusion obtained was that the experimental value against the modeling could be compared well, making this method a unique novelty of this study.

Table 3. Comparison of experimental corrosion rate with the model

Time (days)	Corrosion Rate (mm/year)											
	0 ppm		200 ppm		400 ppm		600 ppm		800 ppm		1000 ppm	
	Exp	Model	Exp	Model	Exp	Model	Exp	Model	Exp	Model	Exp	Model
3	0.32	0.304	0.231	0.242	0.157	0.181	0.168	0.137	0.158	0.115	0.108	0.111
6	0.268	0.237	0.195	0.201	0.131	0.153	0.126	0.113	0.121	0.088	0.068	0.074
9	0.228	0.205	0.168	0.180	0.109	0.139	0.099	0.100	0.084	0.075	0.048	0.059
12	0.192	0.185	0.155	0.167	0.095	0.129	0.094	0.092	0.076	0.067	0.038	0.049
15	0.182	0.170	0.138	0.157	0.094	0.123	0.092	0.087	0.076	0.061	0.032	0.044
18	0.172	0.160	0.135	0.150	0.086	0.117	0.088	0.082	0.076	0.057	0.028	0.039
21	0.162	0.160	0.125	0.144	0.086	0.113	0.088	0.079	0.076	0.053	0.028	0.036
24	0.162	0.144	0.123	0.139	0.086	0.111	0.088	0.076	0.076	0.051	0.028	0.034
27	0.162	0.138	0.122	0.135	0.086	0.106	0.087	0.073	0.076	0.048	0.028	0.031
30	0.162	0.133	0.118	0.131	0.086	0.104	0.088	0.071	0.077	0.046	0.028	0.029

4 Conclusion

In conclusion, a new empirical model equation has been successfully developed to predict experimental data on carbon steel corrosion rate at several concentrations and immersion times in a corrosive 3.5% NaCl solution. The final proposed equation model is $CR(t, C) = [0.451 - 0.0007 \times C + 4.90e^{-7} \times C^2] \times t^{[-0.359 + 0.0006 \times C - 8.48e^{-7} \times C^2]}$, which is generated based on a multilevel regression process. This equation is used to calculate the corrosion rate model at each specific concentration and immersion time. The relative corrosion rate analysis decreases with increasing inhibitor concentration. Therefore, the results of the model against experimental data present good data based on a line graph with a similar trend and equipped with the best average error value of 8.77% at a concentration of 200 ppm.

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