



Salinity, pH, and Temperature Effects on the Corrosion Rate of KI-A Steel Plates

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Abstract

Background: Steel structures at tropical ferry ports deteriorate rapidly, yet field evidence on how salinity, pH, and temperature jointly govern the corrosion rate of shipbuilding-grade steel plates remains limited in eastern Indonesia.

Objective: This study quantifies the corrosion rate of 8-mm KI-A steel plates immersed for two to eight weeks at Hunimua and Galala Ferry Ports, Ambon, and partitions the effects of immersion duration, location, salinity, pH, and temperature.

Methods: Twenty-four coupons were exposed for weight-loss testing in accordance with ASTM G1. Data were analyzed using factorial ANOVA, two-sample *t* tests, and regression analysis at a significance level of 0.05.

Results: Immersion duration had no significant effect ($F = 0.49$; $p = 0.492$), whereas location was highly significant ($F = 33.93$; $p = 0.000$) and explained 62.3% of the total variation. The mean corrosion rate reached 13.15 MPY at Hunimua compared with 7.42 MPY at Galala. Salinity ($p = 0.000$; $R^2 = 60.0\%$) and pH ($p = 0.000$; $R^2 = 46.65\%$) were significant in simple regression analyses but not in the multiple regression model ($p > 0.05$), indicating shared variance.

Conclusion: Salinity and pH, rather than exposure duration, govern the corrosion of KI-A steel in tropical port waters. Cathodic protection and corrosion-resistant materials should be prioritized at high-salinity berths such as Hunimua, and further studies should measure dissolved oxygen, current velocity, and biofouling.

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INTRODUCTION

Corrosion of steel plates in marine environments represents a major concern for the durability and safety of maritime structures. The marine environment, characterized by the presence of chloride ions, seawater, and varying pH levels, promotes the accelerated corrosion of steel structures (Li et al., 2024; Y. Wang et al., 2014). This corrosion shortens service life, deteriorates structural integrity, and increases maintenance expenditures for marine infrastructure such as ships, offshore platforms, and coastal structures (Khodabux et al., 2020; Orlikowski et al., 2022; Y. Wang et al., 2014). Within this broader problem, steel plates used in ferry hulls, ramps, and berth structures are among the components most directly exposed to alternating immersion and the full chemistry of the surrounding water. Accordingly, their behavior under actual port conditions is the specific focus of the present study.

Managing steel corrosion in marine settings calls for several complementary strategies. Relevant measures include the development of corrosion-resistant materials, such as geopolymers and low-alloy steels (Li et al., 2024; Zhao et al., 2024), improved design provisions, and the application of protective measures such as sacrificial anodes (Vignesh & Sathiya, 2024). Continued investigation is essential for developing more durable and sustainable solutions for marine infrastructure and ensuring its longevity and safety in harsh marine environments (Khodabux et al., 2020; Shahedan et al., 2024; Zou et al., 2024). The present study contributes to these mitigation efforts by identifying which water-quality parameter is most strongly associated with the corrosion rate at two contrasting ferry ports, so that protection measures can be appropriately designed for berths where corrosion risk is highest rather than applied uniformly across a port network.

Knowledge of steel-plate corrosion rates under specific harbor conditions is essential for the maintenance and longevity of ferries. The marine environment is particularly aggressive toward mild and low-alloy steels, which are commonly used in offshore structures and port facilities because of their economic advantages (Melchers, 2019; Rojas-Valdivia et al., 2026). The corrosion process in this environment is governed by a complex combination of factors, which complicates the reliable prediction of material loss. Previous work has emphasized the need to account for both abiotic and biotic factors in marine corrosion. For instance, global warming and seawater nutrient pollution can significantly affect the long-term serviceability and structural safety of steel infrastructure in seawater environments (Chaves et al., 2016; Melchers et al., 2025). In addition, the presence of sulfur-oxidizing bacteria (SOB) and sulfate-reducing bacteria (SRB) has been linked to accelerated low-water corrosion (ALWC) of steel piles in harbors (Beech & Campbell, 2008; L. Xu et al., 2025). Therefore, a comprehensive approach to understanding corrosion rates under harbor conditions is essential. This includes considering environmental factors such as seawater temperature and nutrient pollution (Chaves et al., 2016; Melchers et al., 2025), microbial activity (Beech & Campbell, 2008; L. Xu et al., 2025), and changes in pore-solution composition due to carbonation (De Weerd et al., 2019; X. Wang et al., 2025). Of these many influences, the present study deliberately restricts its scope to three parameters that a port operator can monitor routinely and at low cost, namely salinity, pH, and temperature.

Earlier investigations demonstrate that numerous variables govern the corrosion rate of steel in marine environments. Water salinity and temperature are important contributors, but their effects are complex and interact with other environmental parameters. Evidence indicates that increasing salinity from 33.18 to 61.10 ppt can reduce the corrosion rate by 28% (Chohan et al., 2024). By contrast, temperature has been reported as the most prominent parameter, with a 76.13% increase in corrosion rate observed as temperature rises (Chohan et al., 2024). Other studies, however, report that temperature has no significant influence on material behavior in certain tropical and nontropical marine environments (Vera et al., 2018). These contrasting findings illustrate the complexity of the corrosion process and the importance of considering multiple factors simultaneously. In addition to salinity and temperature, other factors such as pH, dissolved oxygen, and oxidation-reduction potential (ORP) also contribute materially to steel corrosion. For instance, a decrease in seawater pH from 8.50 to 7 can lead to a 42.54% increase in corrosion rate (Chohan et al., 2024). Machine-learning studies have identified ORP as having the greatest impact on corrosion rate, showing a positive correlation (Liu & Li, 2023). In addition, environmental factors such as soil resistivity, sulfide concentration, and water alkalinity significantly affect the external and internal corrosion of steel pipes (K. Kim et al., 2023). Collectively, these findings reinforce the need to consider various parameters when studying steel corrosion in marine environments. Taken together, these results are not merely varied but mutually contradictory: Chohan et al. (2024) report that rising salinity lowers the corrosion rate while temperature has the greatest effect, Vera et al. (2018) find temperature to be statistically insignificant in tropical water, and Liu and Li (2023) rank oxidation-reduction potential above both. Three shared limitations may help explain these differences. First, much of this work was performed in synthetic electrolytes or at a single exposure site, so the parameter ranges tested rarely overlap and the results are not directly comparable. Second, salinity, pH, and temperature are often treated as independent factors even though salinity and pH can

covary in coastal waters, making conclusions about any single parameter conditional on the others. Third, few of these studies report a partitioned variance analysis showing how much of the observed variation in corrosion rate can be attributed to each parameter, so the practical relative contribution of each factor remains uncertain. The gap addressed here is therefore an in situ, two-site comparison in which the three parameters are measured simultaneously with corrosion rate and their contributions are statistically partitioned.

A number of investigations report that immersion duration significantly influences the corrosion rate of steel in marine environments. For instance, carbon-steel coupons immersed in a French Atlantic harbor for 1–8 weeks produced a corrosion-product layer consisting of sulfated green rust, lepidocrocite, goethite, and magnetite (Guo et al., 2026; Lanneluc et al., 2015). The composition and thickness of this layer evolve with exposure time and consequently influence the corrosion rate. Other studies, however, report that corrosion rates can increase over time under certain conditions. A study of harbor steel structures exposed to tidal conditions found that initial stimulation by organic matter resulted in localized corrosion and corrosion rates up to 12 times higher than those under unstimulated conditions, with the effect persisting even after nine months of exposure (Marty et al., 2014; Zhou et al., 2026).

Taken together, the preceding evidence points to a common mechanism. During the initial immersion period, corrosion rates are generally greater because the steel is directly exposed to aggressive chloride ions. For instance, in a study of low-alloy steel in a 3.5% NaCl solution, the corrosion rate at 35 atm was significantly higher than at 1 atm during the first 5 days of immersion (Sun et al., 2013). As exposure continues, however, the corrosion behavior becomes more nuanced. The formation of a rust layer becomes an important controlling feature. Although this layer may provide a protective effect, its composition and structure strongly determine the effectiveness of that protection. For instance, during seawater immersion, the rust layer typically consists of an inner black layer composed of iron sulfides and green rust and an outer orange-colored layer of Fe(III) oxyhydroxides (Refait et al., 2020; R. Wang et al., 2025). The presence of certain compounds, such as α -FeOOH, CuO, and Ni-containing compounds, in the rust layer can make it more compact and dense, leading to better corrosion resistance (Han et al., 2024). Accordingly, the corrosion rate does not vary linearly with immersion duration. Initially, the corrosion rate is high but tends to decrease and stabilize over time as a protective rust layer forms. However, the effectiveness of this layer depends on various factors, including environmental conditions and steel composition. Understanding this time-dependent process is critical to developing effective long-term protection strategies for steel structures in marine environments.

Accordingly, this study pursued three specific objectives: first, to measure the corrosion rate of 8-mm KI-A steel plates after two, four, six, and eight weeks of immersion at the Galala and Hunimua Ferry Ports; second, to test whether immersion duration, location, and their interaction affect the corrosion rate; and third, to partition the contributions of salinity, pH, and temperature to the observed variation in corrosion rate.

The principal novelty of this research is its paired field design. Corrosion rate and water quality are measured simultaneously at two ferry ports that share a common climatic regime yet differ in hydrographic setting: one is located inside Ambon Bay, whereas the other is situated on the open coast outside the bay. Because ambient temperature is expected to vary less between the two sites than the other environmental parameters, this design provides a basis for assessing the salinity and pH contributions while accounting for temperature rather than assuming that thermal effects are absent. Theoretically, the study contributes a partitioned variance estimate for tropical port waters and extends the predictive framework of Melchers (2019) to shipbuilding-grade steel plate, adding tropical field evidence to a literature still dominated by temperate and synthetic exposures. Practically, it provides port operators with an evidence-based criterion for determining which berth requires enhanced cathodic protection, representing the principal theoretical and applied benefit that this research is intended to deliver (Rojas-Valdivia et al., 2026).

METHOD

An experimental approach was used to examine the corrosion rate of 8-mm KI-A steel plates under varying underwater conditions. The study employed a two-factor factorial design. The experimental factors comprised immersion duration at four levels—two, four, six, and eight weeks—and location at two levels—Galala and Hunimua. The response variable was the corrosion rate, expressed in mils per year (mpy). Steel grade, plate thickness, coupon geometry, surface preparation, mounting arrangement, and immersion depth were kept consistent at both sites, while salinity, pH, and temperature were measured as uncontrolled covariates because the experiment was conducted in an open natural environment. The immersion durations were selected to span the period over which the corrosion-product layer has been reported to stabilize on carbon steel in seawater (Refait et al., 2020; R. Wang et al., 2025), and the two locations were selected to contrast an enclosed bay with an open coast while holding the climate constant.

Table 1

Classification of the experimental variables

Variable	Type	Level or treatment	Control status
Immersion duration	Independent	2, 4, 6, and 8 weeks	Set by design
Location	Independent	Galala; Hunimua	Set by design
Corrosion rate (MPY)	Dependent	Continuous	Measured by weight loss
Salinity, pH, temperature	Covariate	Continuous	Measured, not controlled
Steel grade and thickness	Constant	KI-A, 8 mm	Held constant
Coupon geometry	Constant	20 x 100 x 8 mm	Held constant
Replication	Constant	3 coupons per cell	Held constant
Mounting and immersion depth	Constant	Identical strip plate rig	Held constant

The study was conducted at Galala Ferry Port, inside Ambon Bay, and at Hunimua Ferry Port, outside the bay. The distance between the two locations is 32.4 km. Figure 1 presents the study locations. The two ports were selected to represent contrasting hydrographic settings within a single climatic regime. Galala is located within the semi-enclosed Ambon Bay, where freshwater input and restricted tidal exchange result in lower salinity, whereas Hunimua faces the open Seram Strait, with unrestricted oceanic exchange and stronger wave action. This contrast makes the two sites suitable for isolating the effects of water chemistry, and the measured characteristics of each site are summarized in Table 2.

Table 2

Environmental characteristics of the two study sites during the exposure period

Parameter	Galala Ferry Port	Hunimua Ferry Port
Hydrographic setting	Inside Ambon Bay, semi enclosed	Outside the bay, open coast
Mean temperature (C)	30.16	30.25
Mean salinity (ppt)	29.94	33.55
Mean pH	7.83	7.96
Salinity range (ppt)	24.80 to 33.40	28.90 to 34.50
Tidal and flow regime	Restricted exchange, low current	Open exchange, higher current
Distance between sites	32.4 km	32.4 km

For immersion testing, the sample preparation procedure used KI-A 8-mm plates cut to dimensions of 20 mm × 100 mm × 8 mm, with a total of 24 specimens for the Hunimua and Galala ports, consisting of 12 specimens per port. Each coupon was subsequently weighed using an analytical balance, and this measurement served as the initial mass of each specimen. A

perforated strip plate was used as the support and secured with a nut together with the KI-A 8-mm coupon. Each strip plate accommodated three specimens representing the designated immersion durations. The prepared assemblies were then immersed at the Galala and Hunimua docks. Each immersion duration was represented by three replicate coupons per port, giving twelve coupons per port and twenty-four coupons in total. Following retrieval, corrosion products were removed from the coupons, which were then rinsed, dried, and reweighed using the same analytical balance used for the initial weighing, following the specimen preparation, cleaning, and evaluation practices specified in ASTM G1 and the mass-loss testing guidance provided in ASTM G31. The corrosion rate was then calculated using Equation (1).

$$CR = \frac{(K \times W)}{(A \times T \times D)} \quad (1)$$

where:

K = Constant (3.45×10^6) mpy

T = Immersion time (hour)

W = Lost weight (gr)

D = Density (gr/cm^3)

A = Surface area (cm^2).

Weekly *in situ* water-quality measurements were obtained using a handheld refractometer for salinity, a digital pH meter, and a digital thermometer. Each instrument was calibrated immediately before every measurement session to ensure the reliability of the field data. The refractometer was zeroed using distilled water and verified with a 35-ppt standard solution; the pH meter was calibrated using a two-point buffer series at pH 7.00 and pH 10.01; the thermometer was checked against a certified reference thermometer in a water bath; and the analytical balance was verified using a Class E2 calibration weight. Three readings were taken for each parameter at the same depth, and the mean was recorded to minimize the effects of instrument drift and reading error. The full calibration protocol is given in Table 3.

Table 3

Measuring instruments and calibration procedure applied before each weekly session

Parameter	Instrument	Calibration reference	Resolution
Salinity (ppt)	Handheld refractometer	Distilled water zero; 35 ppt standard	0.1 ppt
pH	Digital pH meter	Buffer pH 7.00 and pH 10.01	0.01
Temperature (C)	Digital thermometer	Certified reference thermometer	0.1 C
Mass (g)	Analytical balance	Class E2 calibration weight	0.01 g

Data analysis followed a two-factor experimental design. The duration of immersion and location were the two factors evaluated for their effects on the corrosion rate. Analysis of variance (ANOVA) for the factorial experimental design was applied to test the individual effect of each factor on the corrosion rate, as well as the simultaneous effect of both factors on the corrosion rate. All hypotheses were tested at the 0.05 significance level using Minitab statistical software. Before the analysis of variance was interpreted, the underlying assumptions were checked: residual normality was examined using the Anderson-Darling test and a normal probability plot; homogeneity of variance across cells was examined using Levene's test and a residual-versus-fitted-values plot; and independence was examined using a residual-versus-observation-order plot. Model adequacy was additionally assessed using the lack-of-fit test reported for each model, which was not significant in any of the models.

Because the experiment took place under field conditions, the factors of temperature, salinity, and pH could not be controlled. Additional analysis assessed differences in temperature, salinity, and pH between the two research locations using a two-sample t-test. The subsequent analysis evaluated the simultaneous and partial effects of temperature, salinity, and pH on the

corrosion rate using multiple regression. The multiple regression model was specified as $CR = b_0 + b_1 \text{Temp} + b_2 \text{pH} + b_3 \text{Salinity} + b_4 (\text{Temp} \times \text{pH}) + b_5 (\text{Temp} \times \text{Salinity}) + b_6 (\text{pH} \times \text{Salinity}) + e$. All three main effects were retained regardless of their individual significance because they are the parameters the study set out to test, and the three two-way interactions were included to allow for the joint effects reported by Chohan et al. (2024). Because these predictors are natural water-quality variables that may covary, collinearity was assessed using pairwise Pearson correlations and the variance inflation factors (VIFs) of the measured data, which are reported in Table 4. Goodness of fit was assessed based on the percentage contribution of the sequential sums of squares together with the lack-of-fit test.

Table 4

Collinearity diagnostics for the environmental predictors, computed from the thirty two paired measurements in Table 6

Predictor	r with Temp	r with Salinity	r with pH	VIF
Temperature	1.000	0.022	-0.212	1.08
Salinity	0.022	1.000	0.532	1.43
pH	-0.212	0.532	1.000	1.50

As the experiment was performed at operating ports rather than under controlled laboratory conditions, several variables known to influence marine corrosion could not be controlled or measured. These include dissolved oxygen concentration, current velocity and turbulence at the berth, suspended sediment load, tidal range, and the composition of the biofilm and macrofouling that colonized the coupons. Any difference between the two ports that originates from these variables is absorbed into the location factor, which must therefore be interpreted as a composite site effect rather than as a purely chemical effect. This limitation is made explicit so that the location contribution reported in the results is not overinterpreted.

RESULTS AND DISCUSSION

Table 5 presents the experimental results, including the initial weight, final weight after immersion, and weight loss resulting from corrosion. Each sample was immersed for two, four, six, and eight weeks at both ports. Equation (1) was used to calculate the corrosion rate. Mean values were then determined for each sample group. All statistical tests reported below were evaluated at a significance level of 0.05, and the corresponding F values and p values are stated with each result so that the strength of the evidence can be judged directly rather than inferred from the wording.

The measured temperature, salinity, and pH values at both ferry ports, Galala and Hunimua, are reported in Table 6. Each parameter was measured four times per week, after which the weekly average was calculated.

The analysis-of-variance results from the factorial experimental design (Table 7) demonstrated that immersion duration, as well as the interaction between immersion duration and ferry port location (Galala and Hunimua), did not significantly affect the corrosion rate of the 8-mm KI-A steel plates. However, the analysis-of-variance results also indicated that ferry port location had a highly significant effect on the corrosion rate of the 8-mm KI-A steel plates, with an F value significant at the $\alpha = 0.05$ level and a p value of 0.000. The contribution of location to the total variation in corrosion rate was 62.3%, while the contribution of the location factor to the overall model was 98.5%. Accordingly, nearly all the variation accounted for by the model (98.5%) originated from the location factor. Expressed in absolute terms, the mean corrosion rate was 7.42 MPY at Galala, compared with 13.15 MPY at Hunimua. The lack-of-fit test for this model was not significant ($F = 0.86$; $p = 0.510$), indicating that the factorial model adequately represented the observed data.

Table 5

Results of the Corrosion Rate Calculation at the Galala and Hunimua Ferry Ports

Location	Sample	Immersion time (Week)	Sample Number	Initial Weight (gr) (1)	Final Weight (gr) (2)	Lost Weight (gr) (1-2)	Corrosion Rate (MPY)	Mean of Corrosion Rate (MPY)
GALALA	1	2	1	109.33	108.97	0.36	9.065	7.17
			2	108.21	107.87	0.34	8.644	
			3	116.66	116.5	0.16	3.790	
	2	4	1	113.96	113.63	0.33	3.996	6.63
			2	117.08	116.54	0.54	6.375	
			3	100.7	100	0.7	9.518	
	3	6	1	115.56	114.36	1.2	9.561	7.91
			2	118.97	118.08	0.89	6.899	
			3	117.74	116.81	0.93	7.280	
	4	8	1	127.52	126	1.52	8.276	7.95
			2	125.31	123.97	1.34	7.418	
			3	111.43	110.11	1.32	8.162	
HUNIMUA	5	2	1	108.69	108.05	0.64	16.204	13.93
			2	106.21	105.75	0.46	11.902	
			3	119.36	118.77	0.59	13.679	
	6	4	1	108	106.74	1.26	16.047	12.02
			2	109.12	108.07	1.05	13.243	
			3	116.2	115.63	0.57	6.777	
	7	6	1	114.86	113.42	1.44	11.539	11.79
			2	118.99	117.6	1.39	10.774	
			3	117.82	116.15	1.67	13.065	
	8	8	1	113.46	111.01	2.45	14.895	14.85
			2	108.69	106.22	2.47	15.635	
			3	113.73	111.42	2.31	14.012	

Table 6

Measurement Results for Temperature, Salinity, and pH at Galala and Hunimua Ferry Ports

Immersion time (Weeks)	GALALA			HUNIMUA		
	Temperature (°C)	Salinity (ppt)	pH	Temperature (°C)	Salinity (ppt)	pH
2	29.70	29.90	7.75	29.60	32.20	7.96
	30.30	30.50	7.74	33.40	34.50	7.79
	29.90	30.10	7.83	31.00	34.30	7.98
	30.30	30.00	7.83	33.00	33.60	7.94
Mean	30.05	30.13	7.79	31.75	33.65	7.92
4	27.60	30.10	7.64	30.10	34.20	7.99
	31.70	30.90	7.79	30.40	34.10	7.98
	30.30	32.20	7.91	29.50	34.20	7.99
	31.00	28.10	7.76	29.30	34.20	8.00
	Mean	30.15	30.33	29.83	34.18	7.99
6	32.40	28.60	7.77	28.70	33.80	7.97
	29.60	32.00	7.77	30.30	28.90	7.95
	31.50	30.80	7.87	29.20	34.10	8.02
	31.90	28.40	7.81	31.00	32.20	7.74
	Mean	31.35	29.95	29.80	32.25	7.92
8	28.50	29.40	7.86	29.30	34.10	7.96
	29.40	29.80	7.91	29.90	34.10	8.04
	28.90	24.80	7.95	29.60	34.10	7.98

Immersion time (Weeks)	GALALA			HUNIMUA		
	Temperature (°C)	Salinity (ppt)	pH	Temperature (°C)	Salinity (ppt)	pH
	29.63	33.40	8.02	29.70	34.20	8.06
Mean	29.11	29.35	7.94	29.63	34.13	8.01

Table 7

Factorial Analysis of Variance Results

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	3	0,129002	0,043001	11,48	0,000
Linear	2	0,128942	0,064471	17,21	0,000
Location	1	0,127102	0,127102	33,93	0,000
Immersion_time	1	0,001840	0,001840	0,49	0,492
2-Way Interactions	1	0,000060	0,000060	0,02	0,901
Location*Immersion_time	1	0,000060	0,000060	0,02	0,901
Error	20	0,074921	0,003746		
Lack-of-Fit	4	0,013219	0,003305	0,86	0,510
Pure Error	16	0,061701	0,003856		
Total	23	0,203923			

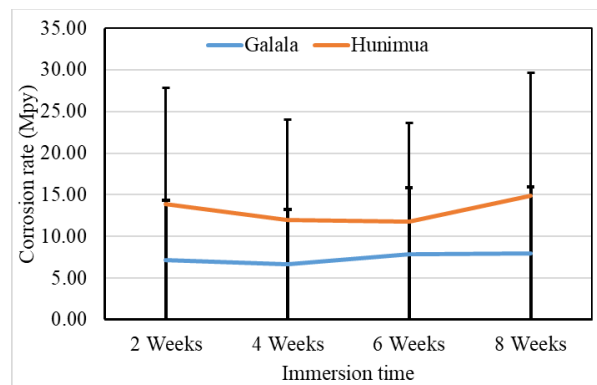


Figure 2. Differences in the corrosion rate of 8mm KI-A steel plates soaked for 2 weeks, 4 weeks, 6 weeks and 8 weeks in the location of the Galala and Hunimua ferry ports

Temperature patterns at the Galala and Hunimua ferry ports are shown in Figure 3, salinity patterns in Figure 4, and pH values in Figure 5. The figures indicate that salinity and pH conditions at Hunimua ferry port are generally higher than those at Galala ferry port, whereas temperature varies without a consistent pattern between the two ferry ports.

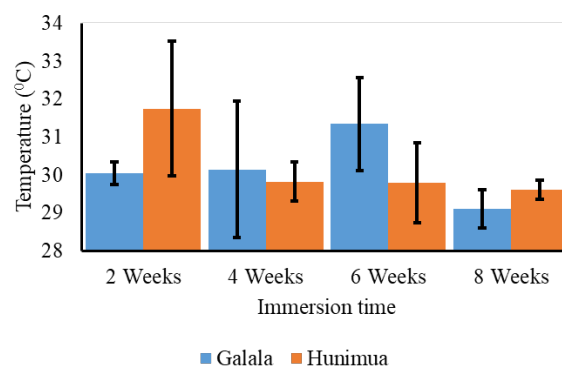


Figure 3. Temperature conditions during immersion of KI-A 8mm steel plates at the Galala (blue) and Hunimua (red) ferry ports

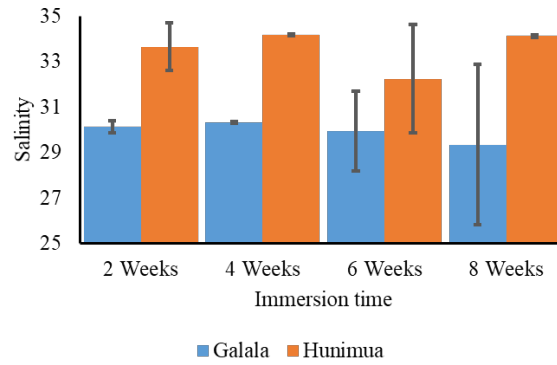


Figure 4. Salinity conditions during immersion of KI-A 8mm steel plates at the Galala (blue) and Hunimua (red) ferry ports.

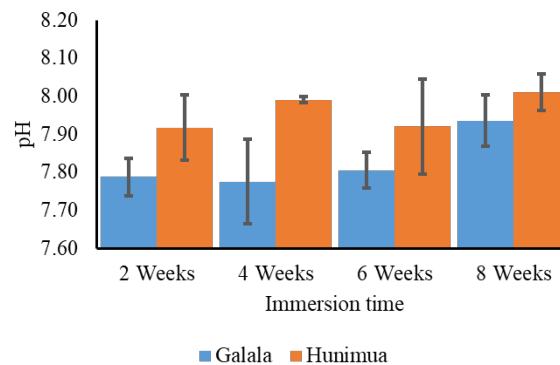


Figure 5. The pH conditions during immersion of KI-A 8mm steel plates at the Galala (blue) and Hunimua (red) ferry ports

To determine whether the conditions differed between the two locations in terms of temperature, salinity, and pH, a two-sample t test was applied. The test results are presented in Tables 8, 9, and 10.

Table 8

T-test Results for the Difference in Mean Temperature at the Galala and Hunimua Locations

Sample	N	Mean	StDev	SE Mean
Temp-1	16	30.17	1.30	0.32
Temp-2	16	30.25	1.31	0.33
Test				
Null hypothesis			$H_0: \mu_1 - \mu_2 = 0$	
Alternative hypothesis			$H_1: \mu_1 - \mu_2 \neq 0$	
T-Value		DF	P-Value	
-0.18		30	0.861	

Table 9

T-test Results for the Difference in Mean Salinity at the Galala and Hunimua Locations

Sample	N	Mean	StDev	SE Mean
Salinity-1	16	29,94	1,96	0,49
Salinity-2	16	33,55	1,41	0,35
Test				
Null hypothesis			$H_0: \mu_1 - \mu_2 = 0$	
Alternative hypothesis			$H_1: \mu_1 - \mu_2 \neq 0$	
T-Value		DF	P-Value	

Sample	N	Mean	StDev	SE Mean
-5,98	30		0,000	

Table 10

T-test Results for the Difference in Mean pH at the Galala and Hunimua Locations

Sample	N	Mean	StDev	SE Mean
pH-1	16	7.8256	0.0932	0.023
pH-2	16	7.9594	0.0827	0.021
Test				
Null hypothesis		$H_0: \mu_1 - \mu_2 = 0$		
Alternative hypothesis		$H_1: \mu_1 - \mu_2 \neq 0$		
T-Value	DF	P-Value		
-4.30	30	0.000		

At the 95% confidence level, the tests indicate that there is no statistically significant difference in temperature between the Galala and Hunimua ferry ports (Table 8), as reflected by a p-value of 0.861. In contrast, significant differences were observed in salinity (Table 9) and pH (Table 10) between the Galala and Hunimua ferry ports, as indicated by a p-value of 0.000. As previously hypothesized, the salinity and pH values at the Hunimua ferry port are higher than those at the Galala ferry port.

To evaluate the combined influence of the three environmental factors on the corrosion rate, a multiple regression analysis was undertaken. The multiple regression results are presented in the ANOVA table shown in Table 7. Because salinity and pH are both governed by the same hydrographic contrast between the two ports, the sequential sums of squares in Table 11 depend on the order in which the predictors enter the model. Therefore, they should be interpreted together with the collinearity diagnostics in Table 4 rather than as independent contributions.

Table 11

Multivariate Regression Test Results

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Regression	6	0.133249	65.34%	0.133249	0.022208	5.34	0.003
pH	1	0.095130	46.65%	0.000001	0.000001	0.00	0.986
Temp	1	0.025798	12.65%	0.000014	0.000014	0.00	0.954
Salinity	1	0.011434	5.61%	0.000582	0.000582	0.14	0.713
Temp*pH	1	0.000234	0.11%	0.000018	0.000018	0.00	0.949
Temp*Salinity	1	0.000399	0.20%	0.000061	0.000061	0.01	0.905
pH*Salinity	1	0.000253	0.12%	0.000253	0.000253	0.06	0.808
Error	17	0.070674	34.66%	0.070674	0.004157		
Lack-of-Fit	1	0.008972	4.40%	0.008972	0.008972	2.33	0.147
Pure Error	16	0.061701	30.26%	0.061701	0.003856		
Total	23	0.203923	100.00%				

Accordingly, separate simple regression analyses were performed to assess the effect of a single factor on the corrosion rate. This approach determines whether there is a significant relationship between each factor and the corrosion rate without the influence or interaction of other factors. The results of the regression analyses are shown in Table 12, Table 13, and Table 14.

Table 12

Results of the Linear Regression Test on the Effect of Temperature on Corrosion Rate

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	0.001747	0.001747	0.19	0.667
Temp	1	0.001747	0.001747	0.19	0.667
Error	22	0.202176	0.009190		
Lack-of-Fit	6	0.140475	0.023412	6.07	0.002
Pure Error	16	0.061701	0.003856		
Total	23	0.203923			

Table 13

Results of the Linear Regression Test on the Effect of Salinity on Corrosion Rate

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	0.12234	0.122344	32.99	0.000
Salinity	1	0.12234	0.122344	32.99	0.000
Error	22	0.08158	0.003708		
Lack-of-Fit	6	0.01988	0.003313	0.86	0.545
Pure Error	16	0.06170	0.003856		
Total	23	0.20392			

Table 14

Results of the Linear Regression Test on the Effect of pH on Corrosion Rate

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	0.09513	0.095130	19.24	0.000
pH	1	0.09513	0.095130	19.24	0.000
Error	22	0.10879	0.004945		
Lack-of-Fit	6	0.04709	0.007848	2.04	0.120
Pure Error	16	0.06170	0.003856		
Total	23	0.20392			

The simple regression results indicate that temperature does not significantly explain variation in the corrosion rate. This is reflected by a p-value of 0.667, which is far above 0.05 (Table 12). By comparison, salinity (Table 13) and pH (Table 14) each show a significant association with the corrosion rate, as reflected by a p-value of 0.000 for each. It should be emphasized that the 60.0% and 46.65% figures obtained for salinity and pH are coefficients of determination from two separate simple regression models. They describe the contribution of each factor in isolation and are not additive: when pH and salinity are entered jointly, their combined sequential contribution is 52.26% rather than the sum of the individual values.

Discussion

As illustrated in Figure 2, although the immersion time of the 8-mm KI-A steel plate was increased, the corrosion rate did not increase significantly, suggesting that factors other than immersion duration influence the corrosion rate. According to Zhang et al. (2021), marine conditions are important, with acidity (pH), chloride ion (Cl^-) content, water flow rate, and temperature all contributing to metal corrosion in seawater (R. Xu et al., 2025). In these studies, it was found that initial corrosion was dominated by pitting corrosion, which later developed into crevice corrosion after a longer immersion period, suggesting that the corrosion pattern depends on the characteristics of the surrounding environment (Al-Moubaraki et al., 2015; Hamza et al., 2025; Rashid et al., 2016). In addition, the results of Zhang et al. (2021) demonstrated that after 28 days of immersion, the electrochemical impedance spectroscopy (EIS) response reached its peak, indicating a slowdown in the corrosion rate due to the formation of a stable corrosion-product layer (R. Xu et al., 2025). Pratama et al. (2021) also reported that after a certain period, the thickness of the corrosion products increased and

provided partial protection to the steel surface (Septe et al., 2026). Research on SUS304 stainless steel in NaCl solution by Rashid et al. (2016) confirmed that after an initial period of rapid corrosion, the corrosion rate stabilized due to the reduced ability of corrosive ions to penetrate deeper into the metal (Alkhaidir et al., 2025). The absence of a significant immersion-time effect in the present data ($F = 0.49$; $p = 0.492$) can be explained mechanistically rather than dismissed as random variation. The weight-loss method integrates all mass lost from the moment of immersion, so a corrosion rate expressed in mils per year is a time-averaged quantity: once a protective corrosion-product layer has formed, the instantaneous corrosion rate decreases, but cumulative mass loss continues to increase at a decreasing rate, and the ratio between the two changes only slightly. In tropical water at approximately 30 °C, inner layers of Fe(II)-based corrosion products and outer layers of Fe(III) oxyhydroxides develop within the first few weeks of exposure (Refait et al., 2020; R. Wang et al., 2025), so by the earliest sampling point at two weeks, the surface was already partially covered. The eight-week observation period used here therefore falls largely within the phase in which the corrosion rate is governed by transport through an established corrosion-product layer, which may explain why the four sampling points do not differ statistically. This also reconciles the present finding with studies reporting the opposite trend: studies that record a strong duration effect either sample within the first few days of exposure, before the protective layer forms (Sun et al., 2013), or extend beyond the point at which anoxic conditions and sulfate-reducing bacteria beneath the corrosion-product layer trigger a second acceleration in corrosion (Marty et al., 2014; Tuck et al., 2022; Zhou et al., 2026). The present result is therefore consistent with, rather than contrary to, the bimodal model of marine corrosion, and it places this experiment within the first plateau of that model. For corrosion prediction under tropical port conditions, the practical implication is that short-term exposure trials may systematically underestimate long-term metal loss unless they are extended beyond the onset of the anaerobic phase.

The Galala ferry port, represented by the blue line, exhibited a lower corrosion rate than the Hunimua dock, represented by the red line (Figure 2). This contrast may be associated with several environmental factors observed in this study, namely temperature, salinity, and pH. This interpretation is supported directly by the statistical evidence rather than by inference alone. The two-sample t-tests show no difference in temperature between the ports ($t = -0.18$; $p = 0.861$), but highly significant differences in salinity ($t = -5.98$; $p = 0.000$) and pH ($t = -4.30$; $p = 0.000$). Temperature can therefore be excluded as a major contributor to the observed difference, and the difference in corrosion rate is more plausibly associated with the chemistry of the two water bodies than with their thermal regime.

Elevated seawater salinity can accelerate corrosion because chloride ions increase the conductivity of the electrolyte and promote localized breakdown of protective surface films. Moreover, Chohan et al. (2024) demonstrated that an increase in salinity from 33.18 ppt to 61.10 ppt led to an increase in the corrosion rate of carbon steel, although this effect may vary depending on other factors such as pH and temperature. The combination of high salinity with other environmental factors, such as water-flow velocity and temperature, increased corrosion rates significantly. In the context of the Hunimua ferry port, which has higher salinity than Galala, the higher chloride concentration may promote the initiation and propagation of corrosion pits and increase the anodic dissolution of iron. Corrosion products formed during this process can include iron(II) and iron(III) hydroxides and oxyhydroxides, which subsequently transform into various forms of rust. Thus, the higher salinity at Hunimua may contribute to the higher corrosion rate compared with Galala, as observed in this study. Quantitatively, the salinity difference between the two ports is 3.61 ppt, from 29.94 ppt at Galala to 33.55 ppt at Hunimua, representing an increase of approximately 12%, yet it is associated with a mean corrosion rate that is roughly 77% higher. The electrochemical reason for this disproportion is that chloride ions do not affect corrosion through simple proportionality. They can adsorb competitively at defects in surface films, promote localized film breakdown, and participate in the formation of soluble iron-chloride complexes. Hydrolysis reactions within localized corrosion sites can further lower the local pH, making pit growth autocatalytic once initiated. Consequently, a modest increase in bulk chloride concentration can produce a disproportionately large increase in localized metal loss. In engineering terms, this means that a

berth such as Hunimua may require a different corrosion-protection strategy from that used at Galala: sacrificial-anode current demand and coating thickness should be designed for the more corrosive exposure condition, and inspection intervals at the higher-salinity berth should be shortened accordingly.

The regression model containing all main effects and interaction terms is statistically significant overall. Thus, the variables considered jointly explain a significant portion of the variation in the corrosion rate. This is demonstrated by the regression p-value of 0.003 at a 95% significance level. However, the p-values for all main factors (pH, temperature, and salinity) and all interactions (temperature $\times$ pH, temperature $\times$ salinity, and pH $\times$ salinity) are high and above 0.05. This finding indicates that none of the main factors or two-way interactions is statistically significant as an individual predictor of the corrosion rate. This seeming inconsistency between a significant overall model and nonsignificant individual predictors is consistent with shared variance rather than with irrelevance of the predictors. The pairwise correlation between salinity and pH in the measured data is 0.532 (Table 4), because both parameters are associated with the same hydrographic contrast: the open-coast water at Hunimua is simultaneously more saline and more alkaline than the semienclosed-bay water at Galala. When two predictors carry largely overlapping information, the regression model cannot attribute the explained variance uniquely to either predictor, so each partial coefficient is estimated with a larger standard error and each individual p-value increases even though the joint model remains significant ([Chan et al., 2022](#); [J. H. Kim, 2019](#)). The variance inflation factors here are moderate rather than extreme, ranging from 1.08 to 1.50, which indicates that severe multicollinearity is not present among the measured variables. However, the variables may still be confounded with the unmeasured site factor: salinity and pH act as proxies for location, and location alone already accounts for 62.3% of the total variation. Tables 7 to 10 should therefore be interpreted as showing that salinity and pH are plausible mechanisms through which location is associated with corrosion rate, while recognizing that the present field design cannot separate their individual effects from the site effect. Separating these effects would require exposure across a controlled salinity gradient at constant pH, which is more appropriately addressed through a controlled laboratory follow-up study rather than through the present field experiment.

The following statements are interpretations that were not experimentally tested in this study and should therefore be treated as hypotheses for future investigation, rather than as empirical findings. Based on the results of this study, it is important to consider the type and composition of the steel plates used. KI-A 8-mm steel plates may have differences in chemical composition or metallurgical properties that affect their corrosion resistance. For instance, if the steel plates used on the ferry docked at Hunimua contained alloying elements or had undergone treatments that improved corrosion resistance, these factors could also contribute to the difference in corrosion rates observed. In this case, further laboratory testing could be conducted to determine and compare the chemical compositions and metallurgical characteristics of the steel plates used at both locations. In addition, environmental factors such as current velocity, as suggested by [Rashid et al. \(2016\)](#), should be considered because stronger water currents can cause mechanical erosion or abrasion of the corrosion-product layer, potentially exposing the underlying steel to further corrosion ([Alkhaidir et al., 2025](#)). For this reason, additional research is required to investigate the influence of current velocity as an environmental factor ([Tuck et al., 2022](#)). To be explicit about the boundary between evidence and assumption, neither the chemical composition of the plates nor the current velocity at the two berths was measured in this study. Therefore, neither factor can be advanced as an explanation for the observed difference on the basis of the present data. Both remain untested candidate mechanisms, and confirming or excluding them would require compositional analysis of the plates, such as spectrometric or spectroscopic analysis, together with continuous current-velocity measurements at each berth.

CONCLUSION

The study results indicate that, at the 95% significance level, the difference in location affects the corrosion rate of the 8 mm KI-A steel plate. Location accounted for 62.3% of the observed variation in corrosion rate. This finding directly addresses the second study objective:

over an eight-week exposure period, the site at which the plate is immersed, rather than the duration of immersion, is the factor associated with the observed corrosion rate.

For Hunimua Port, the 8 mm KI-A steel plate requires more robust corrosion protection. This recommendation is supported by the experimental findings, which demonstrated that Hunimua Port had a higher corrosion rate than Galala Port. This pattern is associated with two measured factors: salinity and pH. When assessed separately, salinity explains 60% of the variation in corrosion rate, whereas pH accounts for 46.65%. Recalculation from the mean corrosion rates reported in Table 1—13.15 MPY at Hunimua and 7.42 MPY at Galala—shows that the corrosion rate at Hunimua is approximately 77.3% higher than that at Galala. Therefore, the figure of 12.45% reported in the original manuscript is inconsistent with the data in Table 1 and should be replaced with 77.3%. These two percentages are coefficients of determination obtained from separate simple regression analyses and describe the explanatory power of each factor in isolation. They are not additive and should not be interpreted as the unique contribution of each variable within a joint model, in which neither variable becomes statistically significant once both are entered simultaneously, as shown in Table 7.

The relatively high salinity and pH values measured in the waters around Hunimua Ferry Port indicate that these environmental conditions are strongly associated with the corrosive behavior of the 8 mm KI-A steel plate.

Overall, the findings show that immersion duration did not directly increase the corrosion rate, whereas environmental factors such as salinity and pH were important in determining the corrosion rate of steel structures in marine environments. Consequently, corrosion-control strategies at ferry berths should focus on mitigating the effects of these environmental conditions, for example, through cathodic protection or the use of materials with higher corrosion resistance. The study contributes scientifically by providing a partitioned variance estimate for tropical port waters, showing that the site effect, expressed chemically through salinity and pH, outweighs the effect of exposure duration over an eight-week period and that the two chemical parameters cannot be readily separated from one another within the range encountered in a single-bay-to-open-coast comparison. The main limitations are the short exposure period, which confines the observations to the initial plateau of the proposed bimodal corrosion model; the modest sample size of three replicates per cell; and the absence of measurements of dissolved oxygen, current velocity, and biological colonization. Future research should therefore extend the exposure period to at least 12 months so that the anaerobic acceleration phase can be captured; add dissolved oxygen, oxidation-reduction potential, current velocity, and biofouling coverage as measured covariates so that the composite location effect can be decomposed; characterize the biofilm and macrofouling communities on the retrieved coupons because microbially influenced corrosion is a recognized driver of accelerated low-water corrosion in harbors and evaluate advanced protection options, such as impressed-current cathodic protection and low-alloy or coated steel plates, under the same field conditions.

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AUTHOR CONTRIBUTION STATEMENT

Rifnia A. Utami contributed to the conceptualization, research design, methodology, experimental work, data collection, data analysis, and preparation of the original manuscript. Agustinus Tupamahu contributed to methodology development, experimental validation, data interpretation, and critical review of the manuscript. Debby R. Lekatompessy contributed to technical analysis, validation, manuscript refinement, and interpretation of the research findings. Richard B. Luhulima contributed to supervision, technical evaluation, critical review, and final manuscript editing.

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