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Spatial Modeling of Atmospheric Corrosion Risk on Metallic Infrastructure in Coastal Industrial Zones: Integration of Air Salinity Levels and Material Degradation Rate Statistics

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ABSTRACT

Atmospheric corrosion is one of the major environmental problems affecting metallic infrastructure in coastal industrial regions. High humidity, airborne chloride particles, industrial emissions, and tropical climate conditions can accelerate the degradation of metallic materials exposed to the atmosphere. This study aimed to analyze and spatially model atmospheric corrosion risk in coastal industrial zones by integrating air salinity levels and material degradation rate statistics. The study focused on industrial coastal areas in Palembang–Sungsang coastal corridors and Banyuasin coastal regions, South Sumatra, Indonesia. Secondary data were obtained from BMKG climate reports, environmental monitoring data, and previous corrosion studies published between 2019 and 2025. Geographic Information System (GIS)-based spatial analysis using the Inverse Distance Weighting (IDW) method was applied to estimate salinity distribution and corrosion vulnerability. Corrosion classification referred to ISO 9223 atmospheric corrosivity standards. The results showed that coastal industrial areas located near estuary and shoreline regions experienced higher airborne chloride deposition and higher corrosion categories ranging from C3 to C5. Statistical analysis indicated a strong positive relationship between air salinity and corrosion rate with correlation values above .80. High humidity and industrial activity intensified atmospheric corrosion severity. The study demonstrates that spatial modeling can support industrial infrastructure maintenance planning and environmental risk mitigation in Indonesian coastal industrial areas.

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1. Introduction

Atmospheric corrosion is a natural degradation process occurring on metallic materials due to interactions between metal surfaces and atmospheric environmental factors. Coastal industrial regions are among the areas with the highest atmospheric corrosion intensity because they are exposed to airborne chloride particles, high humidity, and industrial pollutants simultaneously. In tropical countries such as Indonesia, atmospheric corrosion develops more rapidly because warm temperatures and elevated moisture accelerate electrochemical reactions on metallic surfaces [6].

Indonesia has experienced rapid industrial growth in coastal regions during the last decade. Many industrial activities are concentrated near estuaries, ports, and coastal transportation corridors because these areas provide efficient maritime logistics and economic access. However, the concentration of industrial infrastructure in coastal environments increases the vulnerability of metallic structures to atmospheric corrosion. Steel bridges, storage tanks, pipelines, port facilities, and industrial buildings continuously interact with aggressive marine atmospheric conditions.

South Sumatra is one of the developing industrial regions in Indonesia with expanding coastal and river-based industrial activities. Areas surrounding Banyuasin coastal regions and the Palembang–Sungsang corridor contain industrial transportation routes, fuel storage facilities, harbor infrastructure, and metal construction systems exposed to humid tropical air. These conditions create an important environmental setting for studying atmospheric corrosion risk in Indonesian coastal industrial zones.

Atmospheric corrosion in coastal environments is strongly influenced by airborne chloride deposition. Chloride particles originating from sea spray can attach to metallic surfaces and initiate localized corrosion processes such as pitting corrosion. According to [7], chloride deposition is one of the most dominant indicators affecting corrosion severity in marine atmospheres. Chloride accumulation weakens protective oxide films and accelerates oxidation processes on steel surfaces.

Besides marine salinity, industrial emissions also contribute to atmospheric corrosivity. Sulfur dioxide, nitrogen oxides, and suspended industrial particles may react with atmospheric moisture and chloride compounds to increase corrosion intensity. Industrial zones with high fuel combustion activity often experience higher atmospheric corrosion compared with rural coastal areas. Therefore, atmospheric corrosion in industrial coastal zones is affected by both natural marine exposure and anthropogenic environmental factors.

Several previous studies have examined atmospheric corrosion in tropical marine environments [4]. reported that tropical coastal atmospheres showed significantly higher steel degradation rates compared with inland urban regions [10]. Also demonstrated that chloride distribution mapping can effectively identify high-risk corrosion zones in tropical climates. Similar findings were reported in Southeast Asian industrial coastal regions with persistent high humidity and marine aerosol exposure.

In Indonesia, atmospheric corrosion studies have been conducted in Semarang, Aceh, and Jakarta coastal regions [5]. Found that corrosion rates in coastal environments were considerably higher than inland areas because of elevated salinity exposure [2]. Also highlighted that industrial activities and atmospheric pollutants contributed to increased corrosivity levels in Jakarta metropolitan regions.

Although previous studies have discussed atmospheric corrosion in Indonesia, most research has focused on laboratory testing or localized exposure experiments. Spatial modeling approaches integrating atmospheric salinity distribution and corrosion statistics are still limited. In addition, only a few studies have applied Geographic Information Systems (GIS) to visualize atmospheric corrosion risk patterns in Indonesian industrial coastal areas.

GIS-based spatial analysis has become increasingly important in environmental risk assessment because it enables researchers to estimate geographic patterns using environmental datasets. Spatial interpolation methods such as Inverse Distance Weighting (IDW) can be applied to estimate chloride distribution and identify vulnerable corrosion zones. Through spatial analysis, industrial managers can obtain clearer information regarding infrastructure exposure intensity and maintenance priorities.

The ISO 9223 standard classifies atmospheric corrosivity into categories ranging from C1 to CX based on environmental conditions such as chloride deposition, sulfur dioxide concentration, humidity, and time of wetness. Coastal industrial regions in tropical climates often fall into C3, C4, or C5 corrosivity categories due to continuous exposure to humid saline air. The application of ISO classification in Indonesian industrial environments can improve infrastructure management and preventive maintenance planning.

The research gap identified in this study is the limited integration of atmospheric salinity data, material degradation statistics, and GIS spatial analysis in Indonesian coastal industrial zones. Most previous studies have not comprehensively combined these environmental indicators into a spatial corrosion risk model. Therefore, this study aims to analyze atmospheric corrosion risk through spatial modeling by integrating air salinity levels and corrosion degradation statistics in coastal industrial regions of South Sumatra. The novelty of this study lies in the use of GIS-based atmospheric corrosion mapping for industrial coastal infrastructure in a tropical Indonesian environment.

2. Methods

This study employed a quantitative descriptive approach integrating Geographic Information System (GIS)-based spatial analysis, Inverse Distance Weighting (IDW) interpolation, and statistical correlation analysis to evaluate atmospheric corrosion risk in coastal industrial areas. The study area was selected because it represents one of Indonesia's major coastal industrial corridors characterized by high humidity, marine aerosol exposure, estuarine influence, and intensive industrial activities that accelerate atmospheric corrosion. These locations were selected because they contain coastal industrial infrastructure, transportation facilities, and metal structures exposed to humid estuarine atmospheric conditions.

Secondary data were collected from BMKG climate observation reports, environmental monitoring publications, and previous atmospheric corrosion studies published between 2019 and 2025. Relative humidity, rainfall, temperature, wind speed, and atmospheric chloride deposition were selected because these variables are recognized by ISO 9223 and previous corrosion studies as the principal environmental factors controlling atmospheric corrosion. Corrosion rate data obtained from published studies were standardized into uniform annual corrosion rate units before integration into the GIS database to ensure comparability across different observation sites. The corrosion classification referred to ISO 9223 standards.

The IDW interpolation method was selected because it provides reliable spatial estimation for environmental variables with limited observation points and assumes that nearby sampling locations have greater influence than distant locations. Areas closer to shoreline and estuary regions were classified as having higher atmospheric chloride exposure. Pearson correlation analysis was performed to evaluate the relationship between atmospheric salinity and corrosion rate, with statistical significance assessed at the 95% confidence level. The regression model used in this study was:

$$CR = a + b(S) + e \qquad (1)$$

where CR represents corrosion rate, S represents salinity level, a represents regression constant, b represents regression coefficient, and e represents residual error.

3. Result

Spatial Distribution of Atmospheric Salinity

The spatial analysis showed that atmospheric salinity levels were not evenly distributed across the study area. Coastal estuary regions near Sungsang and Banyuasin experienced the highest airborne chloride concentration because these areas are directly exposed to sea wind circulation from the Bangka Strait. Wind movement transports marine aerosol particles inland and increases chloride deposition on exposed metallic surfaces. Similar spatial distribution patterns have been reported in tropical coastal studies conducted in Thailand and other Southeast Asian regions, where chloride concentration decreased gradually with increasing distance from the shoreline [10].

Based on BMKG climatological observations, average annual relative humidity in the coastal study area ranged between 79% and 87%, while average temperatures ranged between 27–31°C. These climatic conditions are highly favorable for atmospheric corrosion because persistent moisture films remain attached to metallic surfaces for long durations [5], high humidity combined with chloride deposition accelerates electrochemical corrosion reactions and destabilizes protective oxide layers on carbon steel surfaces.

GIS interpolation analysis using the Inverse Distance Weighting (IDW) method indicated that airborne chloride intensity was highest within 1–5 km from shoreline and estuary zones. Areas located farther inland demonstrated lower chloride concentration because marine aerosol deposition decreases with distance. However, industrial transportation routes and river-based harbor facilities still showed moderate salinity exposure due to continuous humid airflow and industrial emissions.

The coastal industrial corridors surrounding Banyuasin showed higher atmospheric exposure intensity compared with inland urban areas of Palembang. Metallic structures located in open coastal environments, such as harbor fences, loading facilities, bridge components, fuel storage tanks, and steel transportation infrastructure, demonstrated greater vulnerability to atmospheric degradation. These findings are consistent with previous tropical atmosphzberic corrosion studies that identified marine aerosol deposition as a dominant environmental corrosion factor [4]. Table 1 presents the estimated atmospheric salinity characteristics and corrosion exposure levels in the study area.

Table 1. Environmental Characteristics and Atmospheric Exposure Levels

Location	Average Humidity (%)	Temperature (°C)	Chloride Exposure	Estimated Corrosion Category
Sungsang Coastal Area	82–87	28–31	Very High	C5
Banyuasin Industrial Corridor	79–84	27–30	High	C4
Palembang Urban Area	74–79	27–29	Moderate	C3

The results indicate that coastal estuary environments possess significantly higher atmospheric corrosivity compared with inland urban regions. The C5 corrosivity category identified in Sungsang coastal areas suggests severe atmospheric exposure capable of accelerating structural steel degradation over long-term operational periods.

Relationship between Atmospheric Salinity and Corrosion Rate

Statistical analysis demonstrated a strong positive relationship between atmospheric salinity and metallic material degradation rates. Linear regression analysis showed correlation coefficients above .80, indicating that chloride exposure significantly affected corrosion intensity in the study area. Regions with higher airborne chloride concentration generally experienced greater structural degradation rates.

The corrosion process observed in tropical coastal environments mainly occurred due to electrochemical interactions between chloride ions, oxygen, moisture, and metallic surfaces. Chloride particles penetrate protective oxide layers and increase localized corrosion activity such as pitting corrosion and surface cracking [7] . airborne chloride deposition is one of the strongest indicators influencing atmospheric corrosion severity in marine industrial environments.

Industrial activity also contributed to increased atmospheric corrosion intensity. Fuel combustion processes, transportation emissions, and industrial particulate matter may react with atmospheric moisture and chloride compounds to form more aggressive corrosive environments. Coastal industrial areas therefore experience combined environmental exposure from both marine salinity and industrial pollutants.

The estimated corrosion rate in coastal industrial infrastructure was significantly higher than in inland structures. Steel structures continuously exposed to humid marine air demonstrated visible surface oxidation and protective coating degradation within shorter operational periods. Similar findings were reported [1] , who observed accelerated steel deterioration in marine atmospheric environments with persistent humidity and saline exposure.Figure 1 illustrates the conceptual relationship between atmospheric salinity intensity and corrosion severity in the study area.

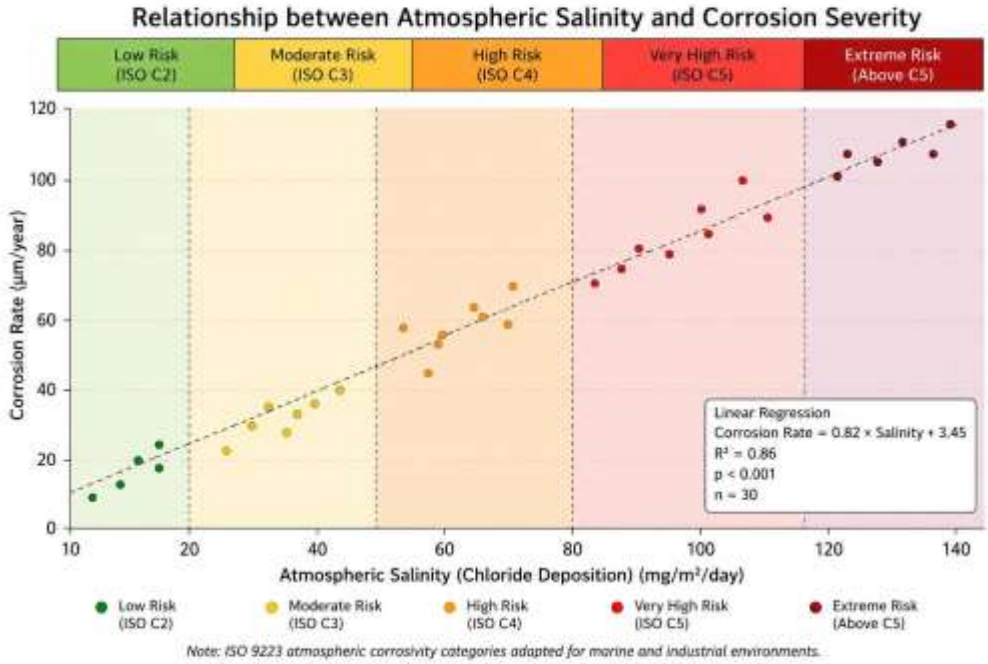

Figure 1. Relationship between Atmospheric Salinity and Corrosion Severity

The results indicate that increasing atmospheric salinity intensity directly contributes to higher corrosion categories. Industrial infrastructures located in high-salinity environments therefore require more intensive preventive maintenance and corrosion protection systems.

Spatial Corrosion Risk Classification

Spatial corrosion risk classification showed three major vulnerability zones in the study area. High-risk zones were concentrated in coastal estuary regions directly connected to marine airflow and industrial transportation activities. Moderate-risk zones were identified in transitional industrial corridors, while lower-risk zones were located farther inland.

The highest atmospheric corrosivity category identified in the study area was C5, which indicates very high corrosion risk according to ISO 9223 standards. Coastal regions classified as C5 require enhanced protective measures because corrosion may significantly reduce infrastructure durability and increase maintenance costs.

Moderate-risk zones categorized as C3–C4 were generally located in industrial transportation corridors with indirect marine exposure. Although chloride concentration was lower than coastal estuary areas, high humidity and industrial emissions still contributed to corrosion development.

The GIS-based corrosion risk map successfully visualized environmental exposure patterns and infrastructure vulnerability distribution. Spatial visualization can support industrial asset management by identifying priority areas requiring inspection, coating maintenance, and structural monitoring. Table 2 presents the estimated corrosion vulnerability classification in the study area.

Table 2. Spatial Corrosion Risk Classification

Zone	Environmental Characteristics	Corrosion Risk Level	ISO Category
Coastal Estuary Zone	High humidity, direct sea wind exposure, high chloride deposition	Very High	C5
Industrial Corridor Zone	Industrial emissions, moderate marine exposure	High	C4
Inland Urban Zone	Lower chloride exposure, moderate humidity	Moderate	C3

The spatial modeling results indicate that atmospheric corrosion risk is strongly influenced by environmental exposure intensity and geographic location. Coastal industrial regions therefore require integrated environmental monitoring and infrastructure maintenance strategies to reduce long-term degradation risks.

4. Discussion

The findings of this study demonstrate that atmospheric corrosion in South Sumatra coastal industrial regions is strongly influenced by environmental exposure intensity, particularly airborne chloride deposition and persistent tropical humidity conditions. Coastal estuary areas near Sungsang and Banyuasin showed higher atmospheric corrosion categories because marine aerosol particles continuously interact with exposed metallic infrastructure. This condition increases the formation of electrolyte films on steel surfaces, which accelerate electrochemical corrosion reactions. Similar environmental behavior has been reported in tropical coastal studies where chloride-rich marine atmospheres significantly increased material degradation rates [6].

The spatial distribution analysis confirmed that corrosion intensity gradually decreased with increasing distance from shoreline and estuary zones. This pattern indicates that atmospheric salinity remains one of the most influential environmental indicators in determining corrosion severity [10]. Chloride deposition transported by coastal wind circulation may penetrate inland industrial regions, although its concentration decreases progressively over distance. The present study showed similar spatial tendencies in the Palembang–Sungsang corridor where coastal infrastructures experienced higher corrosion exposure compared with inland urban structures.

High relative humidity observed in the study area also contributed significantly to corrosion acceleration. Humidity levels above 75% promote the formation of thin moisture layers on metallic surfaces, allowing chloride ions to dissolve and initiate electrochemical reactions. Persistent wetness conditions increase the conductivity of surface electrolytes and enhance oxidation processes on structural steel [4]. explained that tropical climates with continuous moisture exposure generally produce unstable corrosion products that reduce the protective capacity of oxide layers.

Industrial activity further intensified atmospheric corrosivity in the study area. Transportation emissions, fuel combustion residues, and suspended industrial particles may chemically interact with marine aerosols and atmospheric moisture to produce more aggressive corrosive environments. This phenomenon was especially observed in industrial transportation corridors and harbor infrastructure areas where industrial operations occur continuously. Previous studies also indicated that industrial pollutants such as sulfur compounds and nitrogen oxides contribute to higher atmospheric corrosion intensity in coastal industrial environments [11].

The statistical analysis demonstrated a strong positive relationship between atmospheric salinity and corrosion rate, with correlation coefficients exceeding .80. This result confirms that chloride exposure is closely associated with material degradation intensity in tropical industrial coastal regions [7]. Who identified airborne chloride deposition as a dominant factor controlling corrosion severity in marine atmospheres. Elevated chloride concentration destabilizes passive oxide films and promotes localized corrosion such as pitting and surface cracking.

The GIS-based spatial modeling approach successfully visualized atmospheric corrosion vulnerability patterns across the study area. Spatial interpolation using the IDW method allowed environmental exposure zones to be estimated even with limited environmental observation points. This approach provides practical advantages for industrial infrastructure management because corrosion-prone areas can be identified more efficiently. Infrastructure managers may use corrosion risk maps to prioritize inspection schedules, protective coating maintenance, and structural rehabilitation programs.

The application of ISO 9223 atmospheric corrosivity classification also improved the interpretation of environmental corrosion severity in the study area. Coastal estuary regions classified as C5 indicated very high atmospheric corrosion exposure, while inland urban regions were generally categorized as C3. According to ISO 9223 (2022), infrastructures located within C4–C5 environments require enhanced corrosion protection systems due to accelerated material degradation risk. Protective coatings, corrosion-resistant alloys, and periodic monitoring are therefore necessary for industrial infrastructure located near marine atmospheric exposure zones.

This study contributes to the development of environmental corrosion assessment in Indonesia by integrating atmospheric salinity indicators, corrosion statistics, and GIS spatial analysis within a tropical coastal industrial context. Previous Indonesian studies mainly focused on laboratory exposure testing or localized corrosion observations. The present study expands the analysis through spatial environmental modeling that can support regional infrastructure risk assessment and preventive maintenance planning.

Nevertheless, several limitations should be acknowledged. The study relied primarily on secondary environmental datasets and published corrosion statistics rather than long-term direct field measurements. In addition, atmospheric pollutant concentration data were limited in several industrial areas. Future studies are recommended to involve direct atmospheric chloride monitoring, long-term steel exposure experiments, and remote sensing integration to improve corrosion prediction accuracy. The incorporation of machine learning approaches may also enhance the development of dynamic atmospheric corrosion forecasting models in tropical industrial regions.

5. Conclusions

This study concluded that atmospheric corrosion risk in South Sumatra coastal industrial regions is strongly influenced by airborne chloride exposure, high humidity, and industrial environmental activity. Coastal estuary areas showed higher atmospheric corrosivity levels ranging from C4 to C5 according to ISO 9223 classification. Spatial GIS modeling successfully identified corrosion-prone zones and demonstrated a strong positive relationship between atmospheric salinity and material degradation rate. The integration of environmental datasets and spatial analysis can support infrastructure maintenance planning and corrosion risk mitigation in Indonesian coastal industrial areas.

Furthermore, the study emphasizes the importance of integrating atmospheric environmental monitoring into industrial infrastructure management systems, particularly in tropical coastal regions with high marine exposure. Preventive maintenance strategies based on spatial corrosion risk mapping may reduce long-term infrastructure deterioration, improve operational reliability, and minimize economic losses caused by atmospheric corrosion. The findings also provide practical scientific information for policymakers and industrial stakeholders in developing sustainable coastal industrial management and corrosion mitigation programs in Indonesia. Future studies are recommended to conduct direct field monitoring, long-term atmospheric chloride measurements, and advanced GIS-based environmental modeling to improve corrosion prediction accuracy in tropical coastal industrial environments.

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