AIMS Materials Science, 13(3): 560–576.
DOI: 10.3934/matersci.2026027
Received: 22 February 2026
Revised: 22 May 2026
Accepted: 02 June 2026
Published: 17 June 2026

https://www.aimspress.com/journal/Materials

Review

Atmospheric corrosion in H_2S–impacted tropical marine environments: Mechanisms, materials degradation and mitigation strategies–A comprehensive review

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Abstract: Since 2011, recurrent massive strandings of pelagic *Sargassum* across the Caribbean have generated a new class of tropical coastal atmospheres enriched in hydrogen sulfide (H_2S), high humidity, and marine aerosol deposits. These environmental conditions are increasingly recognized as key factors influencing atmospheric corrosion processes and infrastructure durability in affected regions. In this review, we critically synthesized knowledge on the atmospheric corrosion behavior of copper, zinc, and carbon steel in tropical marine environments impacted by *Sargassum*-derived H_2S. Emphasis was placed on reported mechanisms, corrosion product formation, and synergistic interactions between sulfide and chloride species described in the literature. Available studies consistently indicate that H_2S alters conventional corrosion pathways, promoting sulfide-dominated surface layers that are generally porous and weakly protective compared with oxide-based films formed in classical marine atmospheres. We also examined advances in mitigation strategies, particularly bio-derived self-assembled monolayers obtained from *Sargassum* extracts, highlighting their reported protective performance and limitations. By integrating findings from field investigations, published experimental studies, and comparative analyses, we provided a consolidated mechanistic framework and identified key research gaps necessary for improving corrosion prediction and protection strategies in sulfur-impacted coastal environments.

Keywords: atmospheric corrosion; hydrogen sulfide; tropical marine environments; *Sargassum*; carbon steel; copper; zinc; bio-based coatings; self-assembled monolayers

1. Introduction

Atmospheric corrosion is a major degradation mechanism for metals exposed to outdoor environments, occurring under thin and often discontinuous electrolyte films formed via condensation, rainfall, or deliquescence of deposited salts [1–3]. The corrosion kinetics are strongly influenced by environmental parameters such as relative humidity, temperature, airborne pollutants, and the chemical composition of surface deposits [1–3]. Tropical marine environments are recognized as particularly aggressive due to persistently high temperatures, elevated relative humidity, and intense chloride deposition from sea spray aerosols [3–5]. These combined factors often result in accelerated material degradation and reduced service life of metallic infrastructures.

Over the past decade, the Caribbean region has experienced unprecedented and recurrent strandings of pelagic *Sargassum* algae along its coastlines. These events have introduced a novel and increasingly significant source of atmospheric pollution [6–8]. Massive accumulations of stranded *Sargassum* undergo anaerobic biodegradation, leading to the emission of hydrogen sulfide (H_2S) at concentrations that can reach several ppm [6,9]. H_2S readily dissolves in thin surface electrolyte films, altering electrochemical reactions, corrosion kinetics, and the composition of corrosion products [6,10,11]. In tropical marine environments, the coexistence of high humidity, chloride-rich deposits, and sulfur species produces synergistic effects, significantly increasing the aggressiveness of the atmosphere compared to conventional marine conditions [7,12]. In addition to studies conducted in the Caribbean region, investigations performed in other sulfur-polluted and marine atmospheric environments have also highlighted the critical role of H_2S in modifying corrosion pathways and corrosion product stability [13–15]. These studies confirm that sulfide-rich atmospheres promote non-protective corrosion layers and accelerate degradation mechanisms across metallic systems.

Despite increasing field observations of accelerated corrosion in *Sargassum*-impacted coastal areas, a comprehensive synthesis of corrosion mechanisms under these emerging environmental conditions remains limited. We therefore aim to critically review atmospheric corrosion processes affecting copper, zinc, and carbon steel in tropical coastal environments, with particular emphasis on the roles of hydrogen sulfide, chloride ions, and bio-based mitigation strategies using self-assembled monolayers (SAMs) derived from *Sargassum fluitans* III extract [16,17]. We also aim to provide a critical synthesis of the knowledge on atmospheric corrosion mechanisms in tropical marine environments impacted by *Sargassum*-derived H_2S, while identifying key research gaps and emerging mitigation strategies.

2. Tropical marine atmospheres impacted by *Sargassum* strandings

2.1. Origin, accumulation, and anaerobic degradation of Sargassum *algae*

Pelagic *Sargassum* species (*S. natans* and *S. fluitans*) historically developed in the Sargasso Sea, North Atlantic Ocean, where gyre circulation favored their persistence. Since 2011, satellite observations have revealed a large accumulation belt in the equatorial Atlantic north of Brazil, which now serves as a major source transporting biomass toward the Caribbean via surface currents and seasonal winds [2,3]. This redistribution has been linked to ocean warming, circulation shifts, and nutrient enrichment from major river plumes such as the Amazon and Orinoco Rivers [4,5].

When stranded along coastlines, *Sargassum* mats compact, retain moisture, and form thick layers that limit oxygen diffusion, creating strongly reducing microenvironments. Under these anaerobic conditions, sulfate-reducing bacteria metabolize organic matter, producing H_2S that can diffuse into the atmosphere at concentrations reaching several ppm [6,7]. Such levels may exceed recommended exposure thresholds, generate strong odors, and create highly corrosive atmospheres that accelerate metal degradation, particularly in combination with marine salts and tropical humidity [6,8,9].

2.2. Study sites and environmental monitoring

Field investigations in Martinique identified four representative sites to characterize atmospheric corrosion under varying tropical conditions: Frégate-Est (high H_2S), Vauclin (moderate H_2S), Diamant (chloride-rich reference), and Vert-Pré (low H_2S and chloride), as shown in Figure 1 [8,9]. Sites were selected based on proximity to *Sargassum* strandings, frequency of algal deposition, local observations, and safety considerations, representing heavily and minimally impacted environments. Three materials were investigated: copper, pure zinc (99%), and DC01 carbon steel, chosen for their widespread use in industrial and domestic applications. Continuous measurements of H_2S and chloride deposition were conducted using real-time sensors, with H_2S recorded at ten-minute intervals to calculate annual averages and temporal trends. Monitoring revealed four distinct exposure regimes corresponding to the sites, summarized in Table 1. Environmental data presented here are adapted from field studies [8,9].

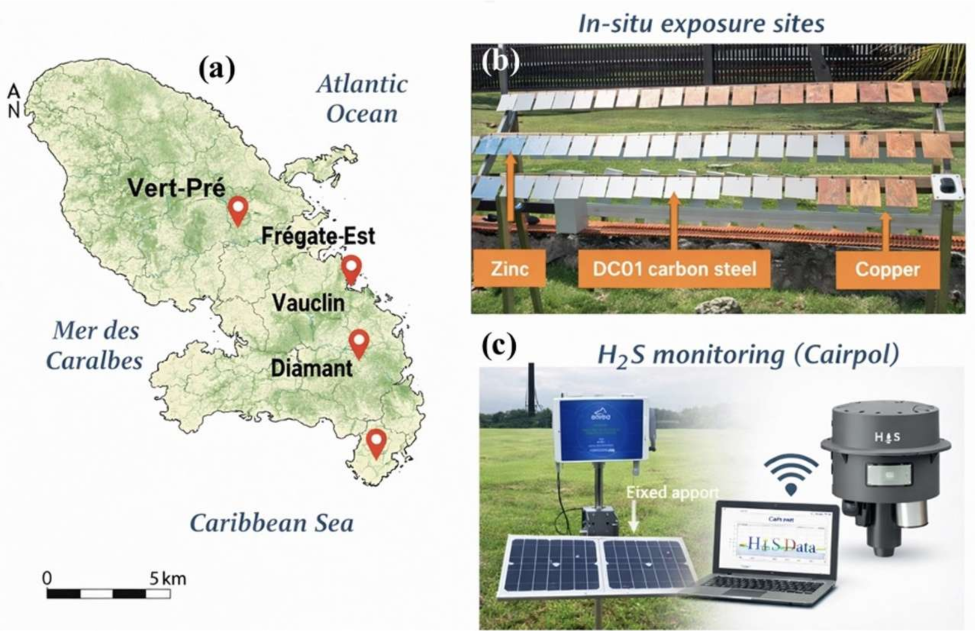


Figure 1. Field study in Martinique: (a) map of sites with/without *Sargassum*; (b) exposure racks with Zn, DC01 steel, and Cu samples; and (c) Cairpol sensors for continuous H_2S monitoring.

Table 1. Annual H_2S and chloride deposition at study sites, illustrating exposure regimes.

Site	H_2S (annual avg)	Chloride deposition (mg m^{-2} day^{-1})	Exposure characteristics
Diamant	~7–10 ppb	481	Chloride-rich marine atmosphere
Vert-Pré	~10–15.5 ppb	46	Low-pollution tropical inland atmosphere
Frégate-Est	~2000–3000 ppb	Low	H_2S-dominated atmosphere (Sargassum influence)
Vauclin	~200–200 ppb	Low	Mixed sulfur–marine atmosphere

3. Atmospheric corrosion of metals in *Sargassum*-impacted environments

In this section, we synthesize findings from studies on the atmospheric corrosion of copper, zinc, and carbon steel in tropical marine environments affected by *Sargassum* strandings. H_2S released during algal decomposition is shown to profoundly alter corrosion pathways, products, and kinetics.

3.1. Copper

Copper corrosion in humid atmospheres is an electrochemical process initiated by the formation of a thin aqueous electrolyte layer. Anodic dissolution occurs via cuprous and cupric species, while cathodic oxygen reduction governs the overall reaction, leading to the formation of cuprite (Cu_2O) [11–16]. This mechanism can be described by Eqs 1–4:

$$Cu \rightarrow Cu^{+} + e^{-} \tag{1}$$

$$Cu \rightarrow Cu^{2+} + 2e^{-} \tag{2}$$

$$O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-} \tag{3}$$

$$2Cu^{+} + 2OH^{-} \rightarrow Cu_2O + H_2O \tag{4}$$

In H_2S-rich atmospheres resulting from *Sargassum* decomposition, sulfide ions strongly interact with copper, producing copper sulfides (CuS, Cu_2S) and hydroxy-sulfates (antlerite, $Cu_3SO_4(OH)_4$) [8–10,17]. These mechanisms can be described by Eqs 5–11:

$$H_2S \rightleftharpoons H^{+} + HS^{-} \tag{5}$$

$$HS^{-} \rightleftharpoons H^{+} + S^{2-} \tag{6}$$

$$Cu + H_2S \rightarrow CuS + H_2 \tag{7}$$

$$Cu^{2+} + S^{2-} \rightarrow CuS \tag{8}$$

$$2Cu^{+} + S^{2-} \rightarrow Cu_2S \tag{9}$$

$$Cu_2S + S^{2-} \rightarrow 2CuS + 2e^{-} \tag{10}$$

$$3Cu^{2+} + SO_4^{2-} + 4OH^{-} \rightarrow Cu_3SO_4(OH)_4 \tag{11}$$

Sulfide- and hydroxy-sulfate-based layers are porous and weakly adherent, offering no effective passivation and explaining the elevated corrosion rates observed in *Sargassum*-impacted atmospheres [8,10].

To better illustrate the evolution of corrosion mechanisms under different atmospheric conditions, Figure 2 schematically compares copper corrosion pathways in chloride-rich and H_2S-rich environments. The diagram illustrates the progressive formation of corrosion products over time, from initial Cu_2O formation to the development of CuS/Cu_2S and basic copper sulfates (e.g., $Cu_3SO_4(OH)_4$). In H_2S-rich conditions, rapid sulfidation dominates, leading to porous and non-protective sulfide layers, whereas chloride-dominated atmospheres favor slower oxide formation and localized basic chloride species. The time evolution from early-stage adsorption to long-term film destabilization is indicated schematically.

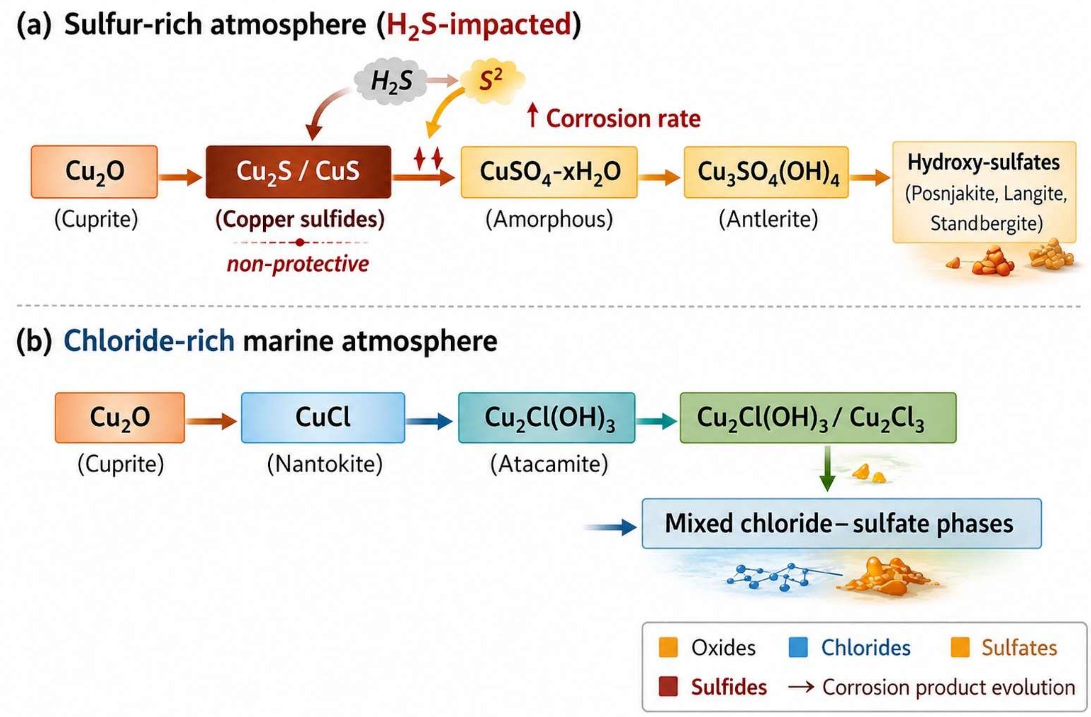


Figure 2. Schematic evolution of copper corrosion over time in (a) sulfur-rich atmospheres from Sargassum H_2S and (b) chloride-rich marine air.

Overall, the literature shows that hydrogen sulfide fundamentally alters the corrosion mechanism of copper, shifting it from an oxide-controlled regime to a sulfur-dominated degradation pathway with non-protective corrosion products and accelerated material loss. This pathway is a key factor in the premature failure of copper components in tropical coastal regions affected by recurrent Sargassum strandings. Figure 2 schematically illustrates copper corrosion under sulfur-rich versus chloride-rich atmospheres, highlighting rapid sulfidation in H_2S-rich environments compared with slower formation of cuprite and basic copper chlorides in chloride-dominated conditions.

3.2. Zinc

Atmospheric corrosion of zinc in marine environments is generally governed by the formation of protective oxide and hydroxide layers [9,18,19]. In conventional marine atmospheres with low H_2S concentrations, chloride ions increase electrolyte conductivity and promote dissolution–reprecipitation processes, sustaining zinc oxidation [18,19]. These processes are commonly described in three key stages:

(1) Anodic and cathodic reactions (oxidation of zinc): this mechanism can be described by Eqs 12 and 13:

$$Zn \rightarrow Zn^{2+} + 2e^{-} \tag{12}$$

$$O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-} \tag{13}$$

(2) Formation of oxide/hydroxide layers: these mechanisms can be described by Eqs 14–16:

$$Zn^{2+} + 2OH^{-} \rightarrow Zn(OH)_2 \tag{14}$$

$$Zn(OH)_2 \rightarrow ZnO + H_2O \tag{15}$$

$$5ZnO + 2CO_2 + 3H_2O \rightarrow Zn_5(CO_3)_2(OH) \tag{16}$$

(3) Secondary corrosion and sulfidation [6,9,20]: this stage of the corrosion process involves the reactions described in Eqs 5 and 6 and the following steps, are presented in Eqs 17–20:

$$4Zn^{2+} + SO_4^{2-} + 6OH^{-} \rightarrow Zn_4SO_4(OH)_6 \tag{17}$$

$$Zn + H_2S \rightarrow ZnS + H_2 \tag{18}$$

$$Zn^{2+} + S^{2-} \rightarrow ZnS \tag{19}$$

$$8\,H_2S + 4O_2 \rightarrow S_8 + 8H_2O \tag{20}$$

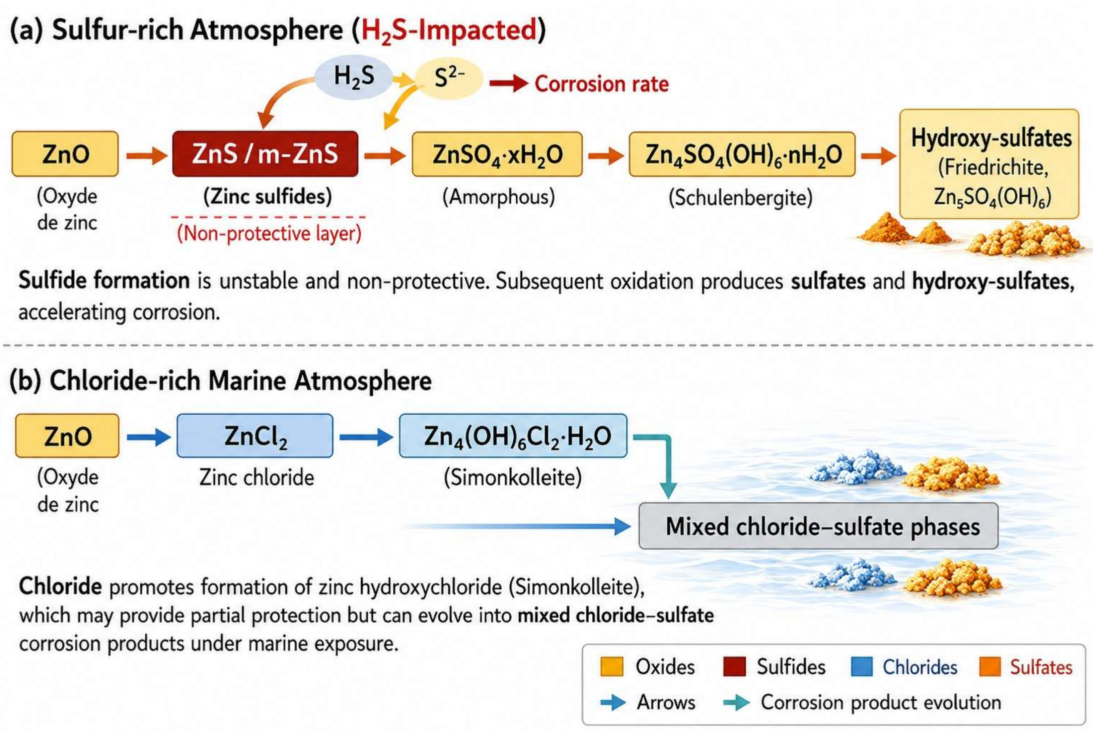
In conventional marine conditions, these reactions produce relatively compact and protective oxide- and hydroxide-based layers, with secondary phases moderating corrosion rates [9,18,19].

In H_2S-rich atmospheres from *Sargassum* decomposition, rapid sulfidation dominates, forming ZnS and elemental sulfur layers that are porous, granular, and non-protective, while chloride-bearing phases are largely absent. Corrosion proceeds nearly linearly over time, resulting in accelerated material loss.

The differences in zinc corrosion mechanisms between conventional marine atmospheres and H_2S-rich conditions are summarized in Table 2 and schematically in Figure 3 [9,20]. In chloride-dominated environments, corrosion proceeds through the formation of $Zn(OH)_2$, ZnO, hydrozincite, and basic zinc salts, which may provide partial protection depending on exposure conditions. In contrast, H_2S-rich atmospheres promote rapid formation of ZnS and elemental sulfur, resulting in porous, non-protective corrosion layers. The table and figure highlight the transition from compact partially protective films to loose granular sulfide deposits as exposure time increases.

Table 2. Comparison of corrosion products, morphology, and corrosion rate of zinc under different atmospheric conditions.

Condition	Main corrosion products	Morphology	Corrosion rate
Marine atmosphere (low H_2S)	ZnO, $Zn(OH)_2$, hydrozincite, simonkolleite, gordaite, zinc hydroxysulfate	Relatively compact and adherent	Moderate
H_2S-rich atmosphere	ZnS (sphalerite), elemental sulfur, zinc hydroxysulfate	Porous, granular, non-protective	Very high



Sulfide formation is unstable and non-protective. Subsequent oxidation produces **sulfates** and **hydroxy-sulfates**, accelerating corrosion.

Chloride promotes formation of zinc hydroxychloride (Simonkolleite), which may provide partial protection but can evolve into **mixed chloride–sulfate** corrosion products under marine exposure.

Figure 3. Schematic evolution of zinc corrosion mechanisms under (a) classical marine conditions and (b) H_2S-rich conditions from *Sargassum* decomposition.

3.3. Carbon steel

Carbon steel corrosion is strongly influenced by chloride and sulfur species. In conventional marine atmospheres, anodic dissolution and cathodic oxygen reduction produce partially protective oxide layers (γ-FeOOH, α-FeOOH, Fe_3O_4) [21,22]. These mechanisms can be described by Eqs 21–24:

$$Fe \rightarrow Fe^{2+} + 2e^{-} \quad (21)$$

$$O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-} \quad (22)$$

$$Fe^{2+} + 2OH \rightarrow Fe(OH)_2 \quad (23)$$

$$4Fe(OH)_2 + O_2 \rightarrow 4FeOOH + 2H_2O \quad (24)$$

In H_2S-rich atmospheres, sulfide ions form FeS-dominated layers that are thick, porous, and poorly adherent, the mechanism at this stage relies on the reactions described in Eqs 5 and 6 [23,24] and the following steps, are presented in Eqs 25–27:

$$Fe + H_2S \rightarrow FeS + H_2 \tag{25}$$

$$Fe^{2+} + S^{2-} \rightarrow FeS \tag{26}$$

$$4FeS + 7O_2 + 2H_2O \rightarrow 4FeOOH + 4S \tag{27}$$

Field investigations in Martinique show that DC01 steel exposed at high-H_2S sites (Frégate-Est) develops thick, porous, black corrosion layers dominated by iron sulfides, while low-H_2S, chloride-rich sites (Diamant) display thin reddish-brown oxide scales with sporadic pitting [9,22–24]. This demonstrates the synergistic effect of H_2S and chloride ions, which accelerates corrosion kinetics in *Sargassum*-impacted tropical atmospheres.

To summarize how atmospheric composition influences corrosion outcomes, Table 3 highlights the major corrosion product trends, morphology, and relative corrosion severity across the studied environments.

Table 3. Summary of carbon steel corrosion behavior in marine atmospheres with varying H_2S and Cl^- exposure.

Exposure condition	Dominant corrosion products	Morphology	Relative corrosion severity
Low H_2S, marine-like (e.g., Vert-Pré)	γ-FeOOH, Fe_3O_4, traces of α-FeOOH	More compact, layered	Lower
Marine with Cl^- influence (e.g., Diamant)	γ-FeOOH, Fe_3O_4	Moderately structured	Moderate
High H_2S (e.g., Frégate Est, Vauclin)	α-FeOOH, γ-FeOOH, magnetite	Rough, less protective	High

Figure 4 represents the evolution of carbon steel corrosion in tropical marine atmospheres under different environmental compositions [25]. Under chloride-rich conditions, corrosion proceeds via formation of iron oxyhydroxides (γ-FeOOH, α-FeOOH) and magnetite (Fe_3O_4), with partial layer compaction over time. Under H_2S-rich atmospheres, rapid sulfidation leads to the formation of FeS-dominated corrosion products, followed by their partial transformation into mixed oxide–sulfide layers. The diagram illustrates the time-dependent evolution from initial anodic dissolution to the development of porous corrosion scales and localized attack (including pitting in chloride-containing systems). The synergistic effect of H_2S and Cl^- is represented by accelerated breakdown of protective oxide films.

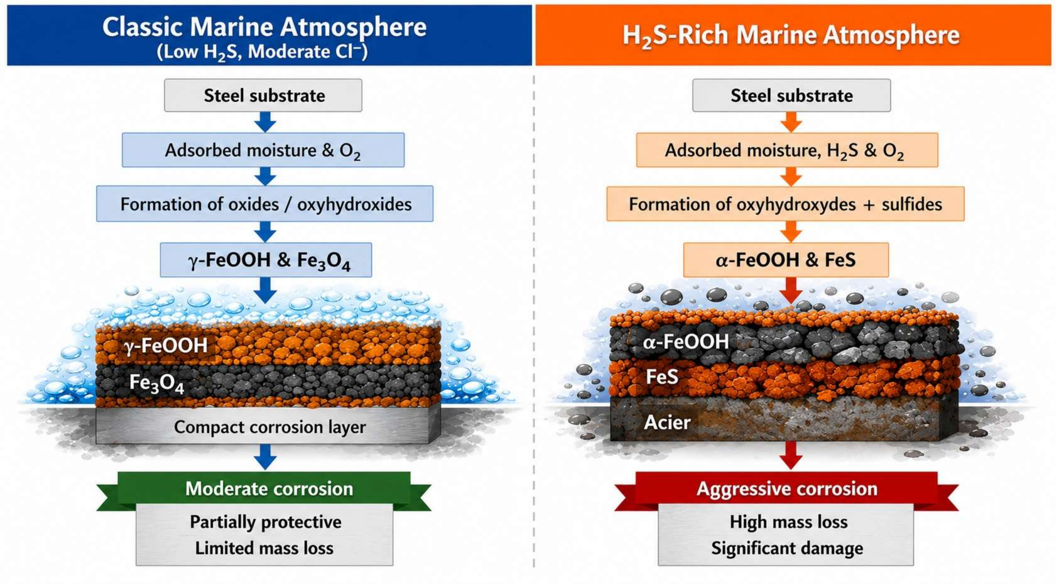


Figure 4. Schematic evolution of carbon steel corrosion pathways under different atmospheric compositions.

3.4. Critical discussion of mechanisms and limitations

The mechanistic descriptions presented in Sections 3.1–3.3 provide a reaction-based interpretation of atmospheric corrosion processes; however, they should be considered within the broader context of coupled electrochemical, chemical, and environmental effects occurring in thin electrolyte layers. A key factor governing corrosion evolution in *Sargassum*-impacted tropical atmospheres is the competition between oxidation and sulfuration pathways. This competition is strongly dependent on the local H_2S/Cl^- ratio. In chloride-dominated marine atmospheres, corrosion is mostly controlled by oxygen reduction and the formation of oxide- and chloride-containing phases, whereas in H_2S-rich environments, the formation of sulfide-rich corrosion products becomes thermodynamically and kinetically favorable [26,27]. This shift in reaction pathway explains the transition from partially protective oxide layers to non-protective sulfide-dominated corrosion products observed in Sections 3.1–3.3.

In addition to bulk atmospheric composition, local physicochemical conditions within the electrolyte film play a decisive role. Under atmospheric exposure, corrosion occurs in thin electrolyte layers where significant pH gradients can develop due to spatial separation of anodic and cathodic reactions and restricted mass transport [28,29]. These gradients influence the solubility and precipitation equilibria of corrosion products, thereby affecting film stability and morphology. Such effects are particularly relevant under intermittent wetting–drying cycles typical of tropical coastal environments.

Furthermore, the presence of biofilms resulting from *Sargassum* decomposition introduces an additional level of complexity. Microbiologically influenced corrosion (MIC) has been widely reported to modify corrosion kinetics through the formation of heterogeneous biofilms that alter oxygen diffusion, trap aggressive ions (Cl^-, S^{2-}), and generate localized electrochemical cells [30,31]. In this context, biofilm development may contribute to spatial variability in corrosion attack and promote the persistence of sulfur-rich microenvironments.

Finally, the stability of sulfide-based corrosion products must be interpreted in terms of thin-film thermodynamics rather than bulk solution equilibrium. In confined electrolyte layers, diffusion limitations and interfacial effects can stabilize metastable phases that would not persist in bulk aqueous systems. This deviation from classical thermodynamic predictions is a well-known feature of atmospheric corrosion systems, where film thickness governs oxygen availability, ion transport, and reaction pathways [32,33]. Consequently, the corrosion products observed in *Sargassum*-impacted atmospheres may reflect kinetically stabilized states rather than equilibrium phases.

Overall, the mechanisms proposed in this study are based on a combination of field observations in tropical marine environments in Martinique and established experimental and theoretical studies from the literature. This dual approach enables the bridging of real environmental exposure conditions with controlled mechanistic interpretations.

4. Discussion: mechanistic insights

The available literature and comparative analyses indicate that atmospheric corrosion in tropical coastal regions impacted by *Sargassum* decomposition is fundamentally different from classical marine corrosion due to the presence of biogenic H_2S, high humidity, and chloride aerosols. Comparative analysis of copper, zinc, and carbon steel (DC01) reveals metal-specific corrosion pathways and synergistic effects between sulfur and chloride species.

4.1. Synergistic effects of H_2S and chlorides

In H_2S-rich atmospheres (Frégate-Est), copper and zinc undergo rapid sulfidation, producing CuS/Cu_2S and ZnS, respectively, while DC01 steel develops iron sulfides in combination with oxide phases [8,9,23,25,34]. These corrosion products generally form porous, granular, and poorly adherent layers, which do not provide effective protection and enable continuous electrochemical activity.

When chloride ions are simultaneously present, as observed in Diamant or Vauclin, they increase the conductivity of the thin electrolyte layer and enhance anodic dissolution as well as oxygen reduction kinetics. This promotes localized corrosion processes, particularly in carbon steel, where heterogeneous sulfide–oxide structures and pitting corrosion are more pronounced. The combined presence of H_2S and Cl^- significantly enhances corrosion kinetics compared to chloride-only environments. Studies conducted for atmospheric and aqueous systems have reported that sulfur-containing environments can increase corrosion rates typically by a factor of approximately 3–5, depending on relative humidity, pollutant concentration, and exposure time [26–28]. Field observations in *Sargassum*-impacted coastal sites in Martinique are consistent with this trend, although variations in magnitude are expected due to local microclimatic heterogeneity and exposure conditions. Independent studies conducted in marine and industrial atmospheres further support these findings. Investigations have shown that sulfur-containing environments significantly modify corrosion product composition, promote the formation of porous sulfide-rich layers, reduce the protectiveness of oxide films, and accelerate overall degradation under combined H_2S and chloride exposure [26,32,33]. In chloride-rich media, additional acceleration arises from the breakdown of passive films and enhanced cathodic reaction kinetics, further intensifying localized corrosion processes in metallic systems [26,27]. A quantitative comparison of corrosion rates across the investigated atmospheric conditions is provided in Table 4, highlighting the progressive increase in corrosion severity from chloride-dominated to

H_2S-rich environments. However, corrosion morphology and kinetics remain strongly dependent on environmental variability, including wet–dry cycling, pollutant concentration, exposure duration, and microclimatic conditions, highlighting the complex and site-dependent nature of tropical atmospheric corrosion systems.

Table 4. Representative corrosion rates in tropical marine atmospheres.

Environment	Copper (µm/year)	Zinc (µm/year)	Carbon steel (µm/year)	Main characteristics
Chloride-rich marine atmosphere (low H_2S)	8–15	10–25	20–50	Oxide/hydroxide films, partial protection
Moderate H_2S + Cl^- exposure	20–40	30–70	60–120	Mixed oxide–sulfide layers, localized attack
H_2S-rich (Sargassum-impacted sites)	40–80	80–150	150–300	Sulfide-dominated, non-protective layers

4.2. Metal-specific mechanisms

- Copper: in chloride-rich atmospheres, Cu_2O and basic copper chlorides form a moderately protective layer. Under H_2S exposure, this layer is replaced by non-protective sulfides, resulting in higher mass loss [17,34]. The corrosion process shifts from an oxide-controlled regime to sulfur-dominated degradation.
- Zinc: the sacrificial behavior of zinc under typical marine conditions is diminished in the presence of H_2S. Formation of ZnS and elemental sulfur deposits disrupts protective oxide/hydroxide films, leading to accelerated uniform corrosion [9,35].
- Carbon steel: DC01 exhibits the highest sensitivity to H_2S, with formation of porous FeS scales that compromise adhesion and promote deeper attack. Chloride deposition further enhances localized corrosion and pitting, resulting in heterogeneous layer formation [23–25].

This conceptual framework provides a unified interpretation of differences in corrosion rates, layer morphology, and metal-specific behavior reported for tropical coastal regions affected by recurrent *Sargassum* strandings.

4.3. Implications for material durability

The literature indicates that *Sargassum*-derived H_2S emissions represent a new corrosive threat for tropical coastal infrastructures. Copper and zinc, widely used in roofing, piping, and electrical components, are vulnerable to accelerated sulfidation. Carbon steel, the primary structural material, is highly susceptible to combined sulfide and chloride attack, leading to reduced service life.

4.4. Conceptual mechanistic model

Figure 5 synthesizes the principal corrosion pathways described in the literature:

- Environment A: sulfur–rich (H_2S-dominated) atmospheres—development of thick, porous sulfide layers on all metals, promoting sustained electrochemical activity and rapid material degradation.
- Environment B: classical chloride–rich marine atmospheres—predominance of oxide or hydroxide layers, providing moderate protection and slower corrosion kinetics.
- Environment C: intermediate H_2S + Cl^- atmospheres—formation of mixed sulfide–chloride layers, resulting in accelerated pitting, heterogeneous corrosion, and moderate-to-high corrosion rates.

This conceptual model integrates the metal-specific mechanisms and synergistic effects of H_2S and chloride, providing a predictive framework for corrosion behavior in tropical coastal environments affected by *Sargassum* strandings.

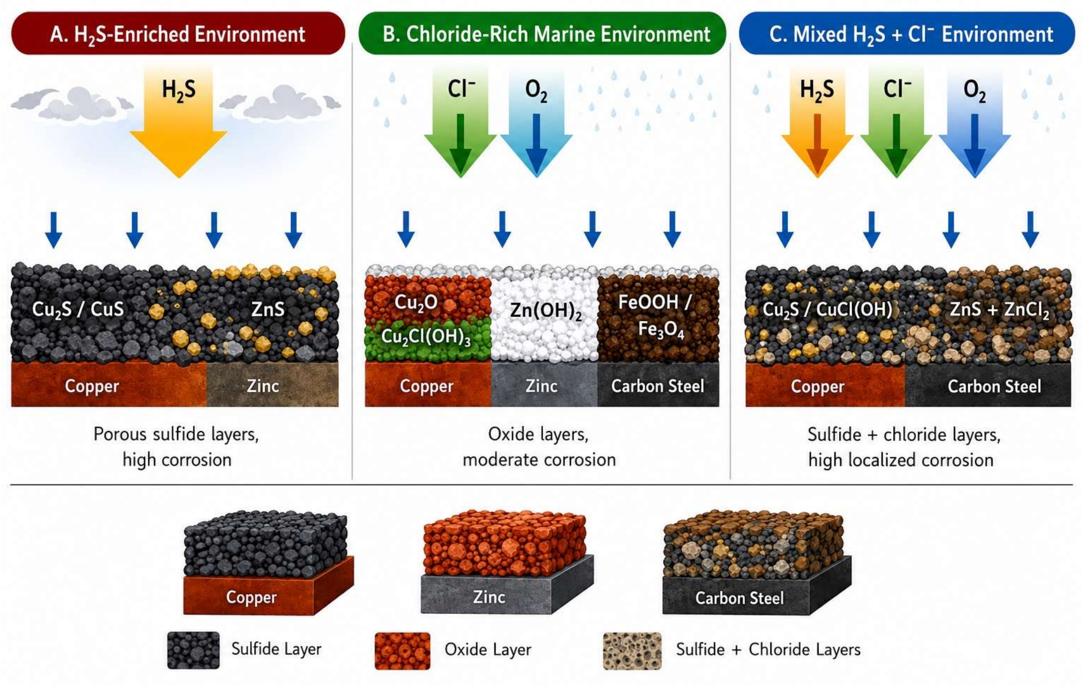


Figure 5. Conceptual schematic of corrosion mechanisms in tropical coastal atmospheres influenced by *Sargassum*-derived H_2S and chloride aerosols.

Overall, comparison of the available literature indicates that the dominant controlling factor governing corrosion behavior in *Sargassum*-impacted environments is not chloride deposition alone, but the combined presence of reduced sulfur species and humidity, which fundamentally alters surface reaction pathways. While chloride ions mostly enhance electrolyte conductivity and promote localized attack, sulfide species directly modify corrosion products and suppress protective oxide formation. Among the metals reviewed, carbon steel appears to be the most sensitive to sulfide-driven degradation, followed by zinc and copper, although ranking may vary depending on local environmental conditions. This comparative analysis highlights that atmospheric chemistry, rather than metal composition alone, is the primary determinant of corrosion severity in these emerging coastal environments.

5. Bio-based SAMs for corrosion mitigation: performance, limitations, and sustainability perspective

Atmospheric corrosion of copper and zinc in tropical marine environments, particularly under H_2S-rich conditions resulting from *Sargassum* decomposition, leads to severe material degradation characterized by the formation of porous oxide- and sulfide-rich corrosion products. Uncoated metals exposed in Martinique exhibit localized and generalized corrosion, with strongly non-protective surface layers dominating under aggressive exposure conditions. Figure 6 summarizes the major corrosion products, their morphology, and relative severity across environmental conditions, providing a framework for evaluating protective strategies.

To mitigate these effects, self-assembled monolayers (SAMs) derived from *Sargassum fluitans* III extract have been investigated as bio-based surface treatments. These SAMs act as ultrathin organic interfacial films that modify surface energetics and partially hinder electrochemical reactions, leading to a reduction in corrosion rates of copper and zinc [36,37]. Reported protection efficiencies range from approximately 50% in chloride-dominated, low-H_2S environments (e.g., Diamant and Vert-Pré) to up to 69% in H_2S-rich atmospheres (Frégate-Est, Vauclin), suggesting a non-linear relationship with environmental aggressiveness.

From a comparative perspective, SAMs provide environmentally benign alternatives to conventional corrosion inhibitors such as chromates or classical organic coatings. However, their protective performance remains limited when compared under identical exposure conditions, particularly in chloride-rich marine atmospheres where thicker organic coatings offer superior barrier properties and mechanical robustness. This highlights an intrinsic trade-off between environmental sustainability and long-term protective efficiency.

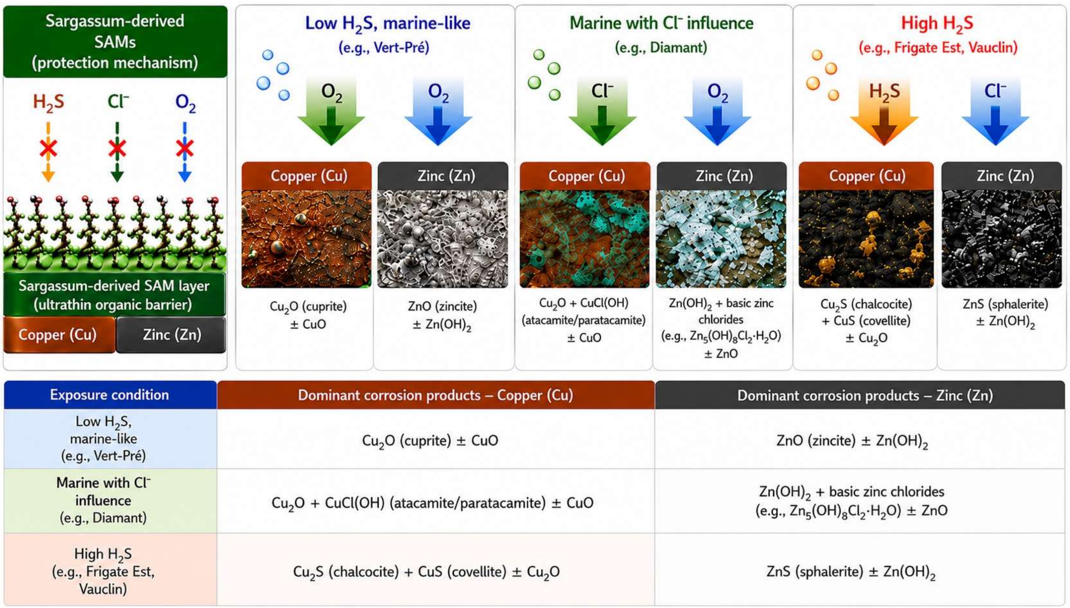
A critical limitation of SAM-based systems lies in their long-term stability and mechanical resistance. Due to their molecular-scale thickness, these films are highly sensitive to abrasion, surface contamination, and localized defects. Once disrupted, SAMs exhibit limited self-healing capability, which may lead to localized breakdown sites acting as initiation points for accelerated corrosion processes such as pitting or crevice corrosion. This aspect is particularly relevant under real exposure conditions involving particulate deposition and wind-driven mechanical stress.

Their performance under combined $H_2S + Cl^-$ exposure, identified as the most aggressive regime in this study, remains only partially understood. While initial inhibition effects are observed, competitive adsorption phenomena and the high reactivity of sulfide species may destabilize the organic layer over time, reducing long-term efficiency.

Additional degradation pathways must also be considered in tropical environments. Photooxidation under intense solar irradiation may alter the chemical structure of organic compounds within the SAMs. Furthermore, microbial colonization and biofilm formation may modify surface chemistry and disrupt molecular ordering. Repeated wet–dry cycling, typical of coastal tropical zones, may also induce progressive desorption and loss of film integrity, further limiting durability.

Finally, from a sustainability perspective, SAMs present an advantage over conventional chromate-based conversion coatings and some industrial organic coatings due to their lower toxicity and potential use of renewable resources. However, this environmental benefit must be balanced against their reduced mechanical durability and shorter expected service life. A life-cycle approach suggests that SAMs may be particularly suitable for short- to medium-term corrosion protection or low-maintenance applications, whereas conventional coatings remain more appropriate for long-term structural protection in highly aggressive environments.

Figure 6 illustrates the overall performance of SAM-coated surfaces compared to uncoated metals, highlighting reduced corrosion rates and more uniform corrosion product layers under tropical exposure conditions.



Exposure condition	Dominant corrosion products – Copper (Cu)	Dominant corrosion products – Zinc (Zn)
Low H_2S, marine-like (e.g., Vert-Pré)	Cu_2O (cuprite) ± CuO	ZnO (zincite) ± $Zn(OH)_2$
Marine with Cl^- influence (e.g., Diamant)	Cu_2O + CuCl(OH) (atacamite/paratacamite) ± CuO	$Zn(OH)_2$ + basic zinc chlorides (e.g., $Zn_5(OH)_8Cl_2{\cdot}H_2O$) ± ZnO
High H_2S (e.g., Frigate Est, Vauclin)	Cu_2S (chalcocite) + CuS (covellite) ± Cu_2O	ZnS (sphalerite) ± $Zn(OH)_2$

Figure 6. Performance of *Sargassum*-derived SAMs in mitigating copper and zinc corrosion in tropical coastal environments.

6. Conclusions

In this review, we provide a comprehensive synthesis of the knowledge on atmospheric corrosion processes affecting metals in tropical coastal environments impacted by *Sargassum*-derived hydrogen sulfide. The literature consistently shows that the presence of reduced sulfur species fundamentally alters conventional marine corrosion mechanisms by promoting sulfide-dominated surface layers that are generally porous, poorly protective, and associated with accelerated degradation.

Comparative analysis of copper, zinc, and carbon steel highlights that corrosion behavior is governed primarily by atmospheric chemistry rather than metal composition alone, with synergistic interactions between sulfide species, chloride deposition, and humidity acting as key controlling factors.

Studies further indicate that bio-derived self-assembled monolayers obtained from *Sargassum* extracts represent promising environmentally sustainable mitigation strategies capable of reducing corrosion rates under aggressive sulfur-rich conditions.

Overall, the findings synthesized here emphasize the need to integrate environmental monitoring, mechanistic understanding, and material protection strategies to improve durability prediction and infrastructure resilience in emerging sulfur-impacted coastal regions. Future research should prioritize long-term field validation, standardized monitoring protocols, and the development of predictive corrosion-risk models applicable to tropical environments.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article. AI tools were used only for language editing and image creation.

Acknowledgments

This research was funded by the Territorial Authority of Martinique (CTM).

Author contributions

Conceptualization: M.L.; methodology: M.S.A., M.L.; software: M.S.A.; validation: M.L.; formal analysis: M.S.A., M.L.; investigation: M.S.A., M.L.; resources: M.L.; data curation: M.S.A.; writing—original draft preparation: M.S.A., and M.L.; writing—review and editing: M.S.A. and M.L.; visualization: M.S.A. and M.L.; supervision: M.L.; project administration: M.L.; funding acquisition: M.L. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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