

Types, Mechanisms, and Efficiency Rate of Galvanized Steel as Corrosion Protection in Atmospheric Corrosion: A Systematic Review

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ABSTRACT Corrosion represents a major concern in numerous industrial sectors, primarily due to the inherent vulnerability of metallic structures to degradation. Therefore, implementing effective corrosion protection measures is essential. Naturally occurring organic chemical compounds and important molecules have demonstrated strong potential for corrosion protection. Some studies indicate that those containing oxygen, sulfur, and nitrogen in the atmosphere exhibit the highest protection performance. Organic and naturally derived protection generally functions by forming protective films on metal surfaces, thereby mitigating the corrosion rate. This review emphasizes the role of galvanized coatings as effective corrosion protection with the cathodic protection method and anode sacrificial on the steel surfaces. It also includes an analysis of steel surface morphology using SEM-EDS micrographs. The review was conducted following PRISMA guidelines, with literature sources covering publications. A total of selected studies were critically analyzed to examine corrosion types, protection mechanisms, efficiency performance, and surface characterization of galvanized coatings. Both Hot-Dip Galvanizing (HDG) and Cold Galvanizing Coatings (CGC) were systematically compared in terms of corrosion rate, protective efficiency, coating thickness, and environmental aggressiveness. The paper systematically covers different types of corrosion, available protection control methods, and corrosion mitigation techniques. It further explores protective mechanisms, evaluates efficiency, and identifies the most effective control strategies. Additionally, the review discusses theoretical approaches, activation parameters, adsorption studies, and surface morphology. This review highlights key factors influencing galvanized steel performance, including coating composition, environmental parameters, and exposure duration, while also identifying current research gaps. The findings provide valuable insights for optimizing corrosion protection strategies and improving the service life of steel structures in atmospheric environments.

KEYWORDS corrosion protection; galvanized protection; SEM-EDS micrographs.

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1 INTRODUCTION

Steel remains a fundamental material in the construction industry, particularly in the development of large-scale infrastructure, such as bridges, industrial complexes, and high-rise buildings. Its high strength-to-weight ratio, versatility, and recyclability make it indispensable in modern engineering applications (Manu et al., 2025). However, due to environmental and chemical exposure, metallic structures are inherently susceptible to degradation over time, primarily through electrochemical corrosion processes. This degradation compromises structural integrity and incurs significant economic costs, estimated at 5–10% of global GDP (Abid et al., 2022). Environmental conditions profoundly affect the safety and long-term durability of buildings in coastal areas, posing a particularly severe threat due to their high potential for accelerating structural deterioration resulting from the corrosion phenomenon (Rahman et al., 2024). This study correlates

with Patah and Dasar (2023), who state that the coastal area, including river sand and tap water, can increase the probability of reducing the durability of buildings due to corrosion. Moreover, corrosion poses significant safety, health, and environmental hazards, especially in high-risk industries, where material failures can result in catastrophic incidents (Dwivedi et al., 2017).

Corrosion profoundly impacts the durability and performance of metallic systems across a broad range of critical sectors, including aerospace, marine engineering, water treatment, biomedical devices, power generation, and resource extraction. As illustrated in Figure 1, the progressive deterioration of metallic materials leads to loss of mechanical integrity and depletion of valuable resources (on the scale of billions of dollars), thereby threatening the sustainability of built infrastructure, accounting for 16.4% from all ma-

for sectors or reaching \$22.6 billion in direct corrosion costs (Zarras and Stenger-Smith, 2014; Anwo et al., 2019). In extreme cases, unchecked corrosion can result in catastrophic structural failures, environmental contamination, and even human casualties (Galleguillos Madrid et al., 2024; Rajendran et al., 2023; Zarras and Stenger-Smith, 2014). Among the various forms of corrosion, atmospheric corrosion remains one of the most widespread and challenging to control. This form of degradation is governed by a complex interplay of environmental variables, including temperature fluctuations, relative humidity, airborne pollutants, and the intrinsic chemical properties of the exposed metal (Tran et al., 2021). Virtually all commonly used metals, including structural steels, exhibit varying degrees of reactivity with atmospheric agents (Shuan, 2016; Manu and Manivannan, 2021).

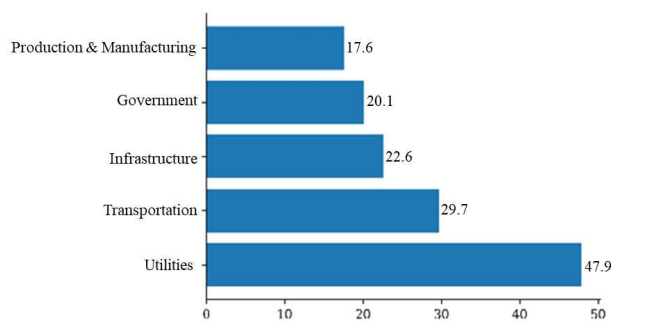


Figure 1. Direct costs of corrosion for five major sectors (modified from Zarras and Stenger-Smith, 2014).

One of the protection methods for steel is through galvanized protection, which utilizes a zinc coating, and is widely employed as a cost-effective corrosion protection strategy. The zinc layer serves as a barrier against environmental exposure, providing sacrificial protection, and making galvanization an efficient solution for corrosion resistance (Shuan, 2016).

The comparative analysis of various zinc-based protective systems in terms of their corrosion rates and protective efficiencies is presented in Table 1. Overall, these findings highlight the variability in corrosion resistance and protective efficiency among different zinc-based protection systems, emphasizing the importance of selecting appropriate formulations based on specific application requirements and environmental conditions.

Understanding the intricacies of atmospheric corrosion of galvanized steel is crucial for predicting its service life, optimizing corrosion protection strategies, and ensuring the structural integrity of the material. The two predominant types of galvanizing protection are Hot-Dip Galvanizing (HDG) and Cold Galvanizing Coating (CGC), both of which offer varying degrees of performance under atmospheric exposure. This review differs in that it systematically evaluates and com-

Table 1. Efficiency and Corrosion Rate with Galvanized or Zinc-based protection

	Protection	Corrosion Rate (mm/y)	Efficiency (%)	Reference
1	Acetyl coumarine (zinc)	0.190	85.000	Minagalavar et al. (2023)
2	Rabeprazole sulfide (zinc)	0.320	98.000	Shanbhag et al. (2011)
3	Hot-dip Galvanized (zinc 85 μm)	0.002	25.950	Vera et al. (2023)
4	Cold Galvanize (zinc-rich)	8.300	86.740	Anyiam et al. (2020)

pares HDG and CGC performance, specifically in atmospheric corrosion contexts. Additionally, we integrate morphological insights from recent SEM-EDS studies, providing a comprehensive understanding of corrosion mechanisms, efficiency rates, and the factors affecting protection longevity. Through a critical analysis of contemporary research efforts, methodologies, and prevailing challenges, the review aims to uncover innovative strategies and forward-looking approaches for mitigating corrosion-related problems across diverse industrial sectors and applications.

2 METHODOLOGY

This literature review was conducted using a systematic review framework, which involved identifying, selecting, evaluating, and synthesizing relevant studies filtered according to a predefined research focus. The review process adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Systematic reviews are widely recognized as a rigorous and effective approach for exploring specific research topics by critically analyzing existing literature and consolidating key findings to support future investigations. This method enables readers to perform comprehensive comparisons and derive well-informed conclusions from the synthesized data, offering a notable advantage over narrative reviews.

2.1 Literature Search Strategy and Keyword Selection

A systematic search strategy targeting literature on galvanized steel as corrosion protection was implemented using two major academic databases: SCOPUS and ScienceDirect. The search process commenced on June 6, 2025. In each database, relevant keywords were applied through the advanced search function, incorporating various combinations as outlined in Table 2. The search was limited to English-language publica-

tions published between 2015 and 2025.

2.2 Filtration of Database

The selection criteria were established in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. Figure 2 presents the inclusion and exclusion criteria applied at each stage of the screening process. An initial total of 4,443 records were identified using the specified keyword combinations. After excluding book chapters, review articles, encyclopedias, conference abstracts, conference information, short communications, and other non-research documents, 485 records from ScienceDirect and 417 from Scopus remained. After removing 646 duplicate entries, 902 unique records were subjected to further screening.

2.3 Data Processing Analysis

This section presents the publication trends of the eligible studies over time, illustrating the number of publications per year. Additionally, keyword analysis was conducted using VOSviewer to identify research patterns and thematic focus areas. A general interpretation of the filtered studies is also provided. Figure 4 summarizes the total number of selected publications between 2015 and 2025.

Table 2. Database keywords, limiters, and primary search results

Database	Terms and limiters applied	Search results (n)
Scopus	Title-Abs-Key (galvanized AND steel) AND (corrosion AND protection) Years 2015–2025 and Limit to Language “English” Article type: Review articles (710) Conference paper (345) Review (24) Book chapter (14) Others (38)	1131
Science Direct	Title-Abs-Key (galvanized steel AND (corrosion protection), Years 2015–2025, and Limit to Language “English” Article type: Review articles (417) Research articles (1998) Encyclopedia (98) Book chapter (665) Others (157)	3312

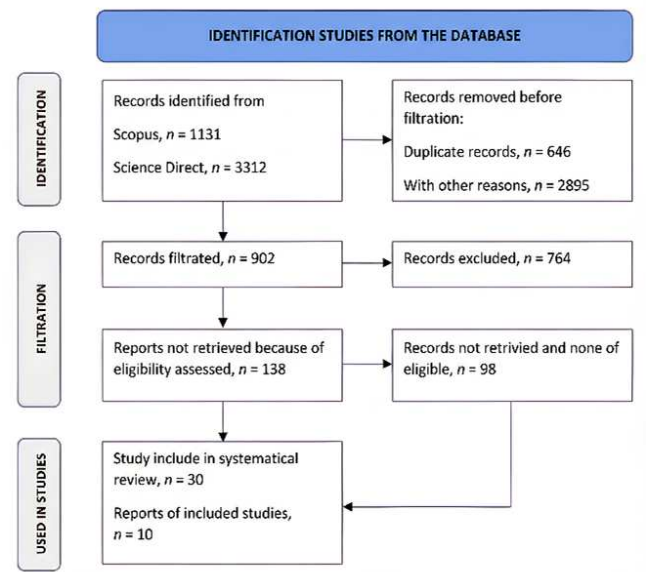


Figure 2. PRISMA statement flow diagram.

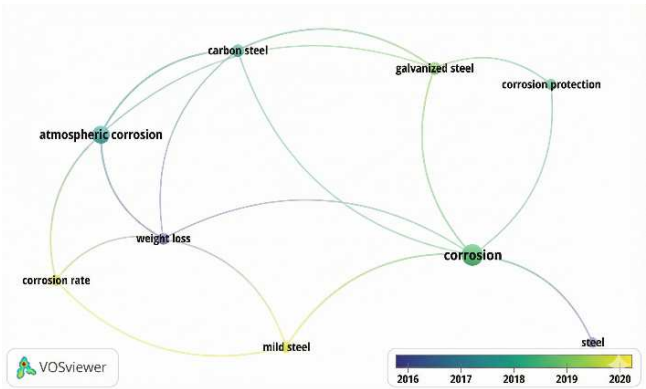


Figure 3. Mapping of references, connectivity of galvanized steel as corrosion protection.

3 FUNDAMENTALS OF CORROSION

3.1 Principle of Corrosion

A variety of parameters influence the corrosion characteristics of metals in aqueous environments. One of the most critical is the hydrodynamic condition; the movement or flow of corrosive fluids can markedly accelerate the corrosion rate of metallic components (Razzaq Tunio et al., 2024).

The surface condition of a material significantly influences both the extent and nature of corrosion. Surface deposits or passive films can act as nucleation sites for localized corrosion, thereby influencing the material’s overall corrosion behavior. Moreover, microbial colonization can alter the local surface chemistry, enhancing metal dissolution. Geometrical features, such as crevices or surface roughness, can facilitate the development of localized microenvironments that concentrate corrosive agents, thereby further promoting

degradation. Additionally, the microstructural characteristics of the material significantly impact surface reactivity and overall corrosion performance (Ibrahimi et al., 2021).

3.1.1 Types of Corrosion

Several types of corrosion exist, comprising:

1. Pitting Corrosion

Pitting corrosion is a highly localized form of attack that results in small cavities or pits on the metal surface. It is typically initiated by aggressive anions, such as chlorides, which disrupt the protective oxide layer and promote localized degradation. Once initiated, pits can propagate rapidly, leading to structural weakness even when the overall material loss appears minimal (KM et al., 2024).

2. Uniform Corrosion

Zarras and Stenger-Smith (2014) described the most common type of material degradation, characterized by a relatively consistent material loss distributed across the entire exposed surface, known as uniform corrosion. It typically results from general exposure to corrosive environments such as moisture, air, or chemical agents. Though it may progress slowly, it is predictable and easier to monitor and control than localized forms.

3. Galvanic Corrosion

This form occurs when two dissimilar metals are electrically coupled in the presence of an electrolyte, resulting in the preferential and accelerated degradation of the more anodic metal. The anodic material experiences increased corrosion activity within this electrochemical system, whereas the cathodic counterpart remains relatively protected (KM et al., 2024).

4. Crevice Corrosion

This type of corrosion occurs in shielded areas where the local environment becomes more aggressive due to restricted fluid movement, such as in joints, gaskets, or beneath deposits. The stagnation leads to a localized depletion of oxygen and an increase in the concentration of corrosion ions, facilitating rapid deterioration (Al-Baghdadi and Alamiery, 2025).

5. Intergranular Corrosion

Intergranular corrosion involves the preferential attack of the surfaces and boundaries of a metal. This can be induced by chemical segregation or the presence of sensitizing elements such as carbon or impurities like chlorine and sulfur. The loss of integrity at grain boundaries can significantly compromise mechanical properties (Ibrahimi et al., 2021).

6. Erosion Corrosion

This type occurs due to mechanical wear and chemical attack caused by high-velocity corrosive

fluids. Commonly found in components such as pipelines, valves, and impellers, it typically manifests as grooves, pits, or scalloped patterns on the surface (Razzaq Tunio et al., 2024).

7. Stress Corrosion Cracking (SCC)

Manu et al. (2025) explained that the SCC condition refers to the formation of brittle cracks in a material exposed to tensile stress while operating in a corrosive environment, commonly known as stress corrosion cracking. It is highly dangerous, causing sudden failure without significant previous deformation. Contributing factors include elevated temperatures, the presence of chlorides, and residual or applied tensile stress.

3.1.2 Schematic Representation of the Corrosion Cycle

Corrosion refers to an electrochemical process in which a material, most often a metal, undergoes gradual degradation, resulting in a reduction of its mechanical strength and structural integrity due to continuous exposure to environmental conditions. From a thermodynamic perspective, corrosion is an exergonic reaction in which metals revert to a more stable, lower-energy state. As a result, metals such as aluminum and iron naturally react with environmental agents like oxygen and moisture, forming hydrated oxides, specifically aluminum oxide and iron oxide, as stable corrosion products. These oxides represent the final stage of material degradation, reflecting a return to the metal's original mineral form as found in nature. The overall progression of this thermodynamically favorable process is illustrated in Figure 4.

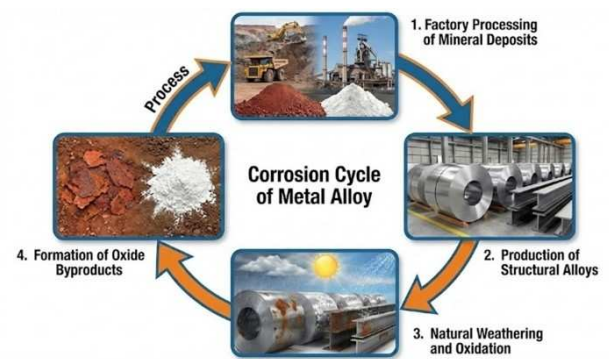


Figure 4. Illustration of the corrosion cycle (modified from Zarras and Stenger-Smith, 2014).

3.2 The Process and Mechanism of Corrosion

Corrosion of Fe-based materials involves the deterioration of their surfaces resulting from chemical or electrochemical reactions in the environment. This process is generally classified into oxidative and elec-

trochemical carbon dioxide (CO₂) corrosion (Narozny et al., 2017; Chen et al., 2023). Water, oxygen, and electrolytes are the primary contributors to Fe-based corrosion. Although CO₂ is theoretically non-corrosive to metals, its supercritical form (sCO₂), often encountered in transport and storage systems, can initiate significant corrosion on Fe-based substrates (Zhu et al., 2019; Yuan et al., 2024). This form of corrosion arises from the formation of carbonic acid, which results when CO₂ dissolves in water.

4 CORROSION PROTECTION

Corrosion protection (also known as anticorrosion or anti-corrosion measures) refers to modifying a corrosion system—to slow down or prevent damage from electrochemical or chemical reactions—by altering the environment, material, or electrode surfaces (Verma et al., 2021). These measures play a vital role in industries such as chemical manufacturing, where the integrity of metal components is crucial. By altering the electrochemical reactions at the surface of metals, these measures suppress or slow down the oxidation process of metals, thereby extending the service life of critical infrastructure (Chitra et al., 2010).

From an electrochemical perspective, corrosion protection is generally classified into three main categories based on their mechanism of action: (a) anodic protection, which interferes with the anodic dissolution of metal; (b) cathodic protection, which reduces the cathodic reaction rate; and (c) mixed protection, which influences both anodic and cathodic processes simultaneously (Vaysburd and Emmons, 2004). This classification aids in strategically selecting protection tailored to specific corrosive environments and application needs.

4.1 The Protection of Hot-dip Galvanized

Hot-dip galvanizing (HDG) is widely employed across various sectors, such as industrial environments with aggressive conditions, due to its ability to protect Fe-based metals from corrosion through both barrier protection and galvanic mechanisms. HDG serves as an effective corrosion protection method for steel, playing a vital role in numerous industrial applications (Marder, 2000). This process involves immersing steel components into a molten zinc bath, where a durable protective layer is formed on their surfaces. During the HDG process, chemical reactions occur between the steel substrate and molten zinc, resulting in the formation of iron-zinc (Fe-Zn) intermetallic phases (Hirose et al., 2003; Culcasi et al., 1999). However, these Fe-Zn intermetallic layers tend to be brittle. To mitigate the formation of these brittle phases, aluminum is added to the zinc bath, using a composition based on the Fe₂Al₅ layer, which acts as a barrier (Shawki and

Hamid, 2003; Syahbuddin et al., 1998). Additionally, including lead in the bath reduces viscosity and surface tension, enhancing the coating's adhesion to the steel substrate. Lead also influences the morphology of the spangle, a characteristic crystalline pattern on the galvanized surface, which leads to dendritic growth with shiny or dull appearances, depending on macroscopic observation. Despite these benefits, the use of lead is increasingly limited due to its effects on human health and the environment (Wang et al., 2008; Pavlidou et al., 2005).

Recent research has expanded the understanding of how various factors influence the performance of HDG coatings. For instance, studies have demonstrated that the composition of the zinc bath plays a crucial role in determining the corrosion resistance of galvanized steel (Chaouki et al., 2025). Alloying elements have been incorporated into the zinc bath to enhance the coating's protective behavior, thereby improving mechanical integrity and electrochemical stability (Zhang et al., 2020). These advances reflect a broader effort to refine HDG processes to meet the increasing performance expectations of contemporary industrial applications.

In addition to coating composition, environmental exposure conditions remain a significant factor in HDG performance. Investigations into the electrochemical corrosion of HDG coatings in simulated concrete environments with varying pH levels have revealed strong corrosion resistance, largely attributed to the formation of passive layers under alkaline conditions typical of concrete (Xie et al., 2017). However, chloride ions, commonly introduced through deicing salts or marine environments, can disrupt this passivation, accelerating localized corrosion. Research by Co et al. (2023) has specifically focused on the interaction between chlorides and galvanized coatings, highlighting the importance of understanding ion transport mechanisms in concrete to improve long-term protection strategies for reinforced steel.

4.1.1 Process of Galvanizing

According to the process, HDG is composed of several steps (Shibli et al., 2015):

1. Substrates Selection
The chemical composition of the steel substrate plays a critical role in influencing both the HDG process and the functional properties of the resulting zinc coating.
2. Base Surface Preparation
One of the critical steps in HDG is that zinc requires a thoroughly clean steel surface to form a proper metallurgical bond, which is achieved through cleaning processes, including degreasing, pickling, and fluxing.

3. Galvanization of HDG Coating

During the HDG process, the steel substrate is prepared for immersion in a zinc bath that is at least 98% pure zinc. The bath composition follows the ASTM specification, part B6, and the temperature is maintained at around 450 °C. At this temperature, zinc reacts metallurgically with the iron in the steel substrate, forming a zinc-iron intermetallic alloy layer. After immersion, the steel articles are carefully withdrawn, allowing excess zinc to be removed through draining, vibration, or centrifugation, and then immediately cooled in air to finalize the coating.

The HDG process is not uniform across studies, and variations in substrate composition, surface preparation, and bath chemistry have a significant impact on coating performance. Shibli et al. (2015) emphasized substrate selection and pre-treatment as decisive factors for metallurgical bonding, whereas Hirose et al. (2003) and Culcasi et al. (1999) highlighted the brittle nature of Fe-Zn intermetallics, which may compromise durability. More recent investigations have introduced aluminum and magnesium alloying to stabilize the Fe₂Al₅ barrier layer, thus improving adhesion (Shawki and Hamid, 2003). However, the inclusion of lead, once reported to reduce viscosity and enhance spangle morphology, is increasingly restricted due to health and environmental risks (Wang et al., 2008). These contrasting findings reveal an inherent trade-off between coating quality and environmental sustainability, underscoring the need for more environmentally friendly alloying strategies. Such comparative analysis indicates that optimizing HDG requires balancing mechanical integrity, corrosion resistance, and ecological impact rather than relying on a single processing variable.

4.1.2 Corrosion and Efficiency Rate of Hot-dip Galvanized as a Corrosion Protection

Several studies conducted in recent years have investigated the atmospheric corrosion behavior of iron specimens protected by HDG coatings, as summarized in Table 3.

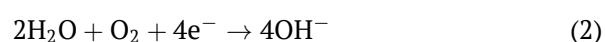
According to the studies by Vera et al. (2023) and Vera et al. (2019), the corrosion performance of HDG-coated steel was compared with that of uncoated (non-protective) steel in CX atmospheric corrosion conditions over a three-year exposure period. The experiments show that the HDG coating reduced corrosion with efficiency rates of 25.95% and 27.97%, respectively, compared to the uncoated specimens. The differences in values between the two could be due to variations in environmental parameters and exposure locations. Additional experiments by Vera et al. (2013), Shiri and Rezakhani (2020), and Del Angel et al. (2015)

evaluated HDG-coated specimens under atmospheric corrosion over shorter exposure durations of 1.25, 1, and 2 years, respectively. These studies reported corrosion inhibition efficiencies of 2%, 5.02%, and 3% compared to uncoated steel under similar environmental conditions. The efficiency of protection against corrosion rates on HDG coatings can be very good due to the galvanization process, which involves a hot-dip zinc coating with a zinc composition of at least 98%. A sufficiently thick coating provides good protection against corrosion, especially in atmospheric environments. The results obtained in Table 3 support this view regarding the correlation between the process and corrosion results.

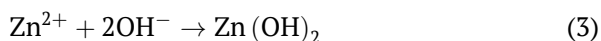
4.1.3 Corrosion Mechanism of HDG

To gain a more comprehensive understanding of the corrosion behavior and clarify the fundamental mechanisms occurring within the spangle structure, cross-sectional examinations were conducted using Scanning Electron Microscopy (SEM) in conjunction with Energy Dispersive X-ray Spectroscopy (EDS). The η -phase layer was not fully depleted in either the shiny or dull spangle samples, indicating that corrosion during short-term immersion was limited to the consumption of this outermost layer. Notably, the η -phase in the dull spangle sample exhibited a higher corrosion rate than that of the shiny spangle, suggesting differences in surface morphology or microstructural characteristics that influence corrosion resistance (Peng et al., 2010).

Drawing from the previous analysis, the electrochemical corrosion behavior of spangle during short-term immersion in NaCl solution can be conceptually segmented into three sequential phases. To illustrate this progression, a schematic model is proposed in Figure 5. As depicted in Figure 5a, the zinc coating displays a characteristic lamellar microstructure, initially covered by a surface film composed of oxides and hydroxides. In Stage I, corrosive species such as O₂, Cl⁻, and H₂O gradually diffuse through this surface film, which readily deteriorates under the influence of the aggressive environment. In Stage II, the corrosive medium penetrates the degraded surface film and reaches the exposed η -phase, initiating active dissolution of zinc. The continued presence of aggressive species facilitates this process, which is further accelerated by the catalytic effect of β -Sb₃Zn₄ precipitates, as illustrated in Figure 5b. The corrosion behavior of the zinc coating in aerated NaCl solution at this stage is governed by the following electrochemical reactions (Mouanga and Berçot, 2010; Hamlaoui et al., 2008):



This process results in the release of Zn^{2+} ions into the solution. In the presence of hydroxide ions (OH^-), the subsequent formation of porous zinc hydroxide can be anticipated by:



In Stage III, an increased accumulation of corrosion formations is identified at the spangle surface. Despite this coverage, the immersion period proceeds concurrently across the surface layer, and the underlying zinc matrix continues to undergo corrosion due to the product layer's porous nature and partial solubility or hydration, as illustrated in Figure 5c. The zinc layer is already degraded by atmospheric conditions; however, it is essential to note that these corrosion stages do not occur sequentially or in isolation, but rather proceed concurrently across different regions of the surface throughout the immersion period.

4.1.4 Corrosion Characterization of HDG

In the characterization of HDG steel for corrosion protection, SEM combined with EDS is commonly used as an analytical tool, especially to examine the surface

morphology. The formation of morphological steel surfaces provides important information regarding the types, mechanisms, and corrosion rates.

Experimental studies by Vera et al. (2023), Vera et al. (2013), and Vera et al. (2019) have demonstrated that HDG steel surfaces develop corrosion products identified as zincite (ZnO) and simonkolleite ($\text{Zn}_5(\text{OH})_8\text{Cl}_2 \cdot \text{H}_2\text{O}$) through XRD analysis. Simonkolleite is primarily observed in micrographs as lamellar, platelet-like structures. EDS analysis reveals that the principal elements in the corrosion products consist of approximately 80.0% zinc (Zn), 12.6% chlorine (Cl), 3.5% oxygen (O), and 1.5% silicon (Si). The presence of silicon is commonly attributed to soil contamination during outdoor exposure tests. These findings are consistent with other studies, which show that atmospheric chloride enhances the formation of simonkolleite on galvanized steel surfaces.

Slightly differing from other experimental findings, studies by Shiri and Rezakhani (2020) and Del Angel et al. (2015) reported an unexpectedly high chlorine

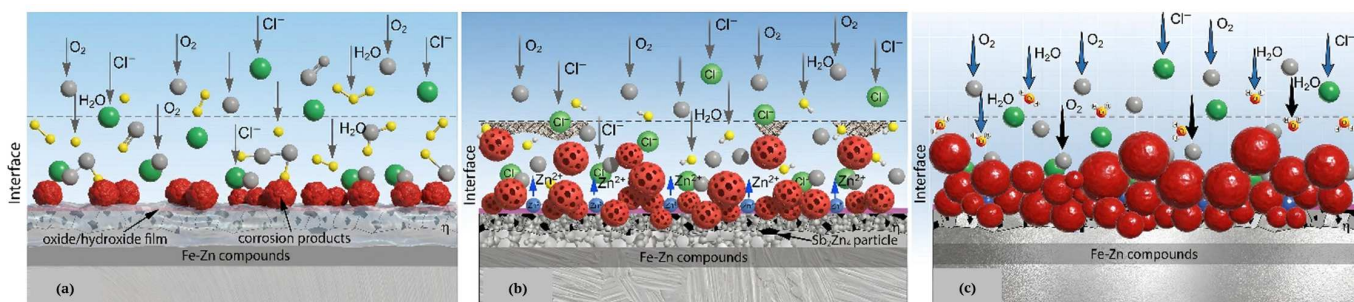


Figure 5. The illustration of the spangle mechanism of zinc corrosion: a) zinc covered by a surface film composed of oxides and hydroxides; b) zinc coating in aerated NaCl solution covered by electrochemical reactions; and c) immersion period proceeds concurrently across the surface layer (modified from Peng et al., 2020).

Table 3. Corrosion and Efficiency Rate of HDG Protection

Case	Protection	Location (Aggressiveness)	Exposure Time (year)	Corrosion Rate (mm/year)	Efficiency Rate (%)	References
1	HDG 85 μm layer-thick	Atmospheric Corrosion (CX)	3	0.0020	25.950	Vera et al. (2023)
	No protection			0.0519		
2	HDG 80 μm layer-thick	Atmospheric Corrosion (C5)	1.25	0.0085	2.000	Vera et al. (2013)
	No protection			0.0170		
3	HDG 85 μm layer-thick	Atmospheric Corrosion (CX)	3	0.0106	27.972	Vera et al. (2019)
	No protection			0.2965		
4	HDG 20 μm layer-thick	Atmospheric Corrosion (CX)	1	0.1025	5.020	Shiri and Rezakhani (2020)
	No protection			0.5146		
5	HDG 9.9 μm layer-thick	Atmospheric Corrosion (C4)	2	0.0030	3.000	Del Angel et al. (2015)
	No protection			0.0090		

concentration on the surface of HDG steel sheets after atmospheric exposure. The elevated presence of chloride ions is believed to significantly contribute to the increased corrosion rate observed in these specimens. In addition to the chloride-containing compound simonkolleite ($\text{Zn}_5\text{Cl}_2(\text{OH})_8 \cdot \text{H}_2\text{O}$), a carbonate-based corrosion product— $\text{Zn}_5(\text{CO}_3)_2(\text{OH})_6$, was also identified on the HDG steel surface. Under natural environmental conditions, this carbonate compound commonly develops on zinc surfaces, particularly within the inner strata of the corrosion product layer. Its initial formation is notably accelerated by exposure to humid atmospheric conditions. Furthermore, it has been noted that even categories of chloride classified as S1 by ISO 9223 ($3 < \text{S1} \leq 60 \text{ mg m}^{-2} \text{ day}^{-1}$) are sufficient to initiate the formation of simonkolleite ($\text{Zn}_5\text{Cl}_2(\text{OH})_8 \cdot \text{H}_2\text{O}$).

4.2 Cold Galvanizing Protection

Cold galvanizing is a protective coating technique in which a Zinc-Rich Paint (ZRP) or compound is applied to the surface of steel or other metals to inhibit corrosion. Unlike HDG, which requires high-temperature immersion of metals in molten zinc, cold galvanizing is performed at or near room temperature through brushing, spraying, or painting a Zinc-rich coating onto the substrate (Spennemann, 2021).

ZRP represents a fundamental element in cold galvanized coatings (CGC), which are widely applied as anti-corrosive treatments for ferrous materials. Serving as an alternative to HDG, ZRP can function as primers, topcoats, or repair coatings for galvanized steel, delivering effective protection in environments of moderate corrosivity. Moreover, ZRP provides cathodic protection to steel substrates, particularly in harsh marine atmospheric conditions (Abreu et al., 1996; Tang et al., 2024). Commonly referred to as cold galvanizing, these coatings have also proven effective in protecting steel structures that are fully or partially submerged in seawater, such as ship hulls, offshore platforms, and jet-ties (Zhang, 1996).

CGC is a single-component zinc-rich formulation, specifically engineered to protect steel substrates from corrosion. To provide effective cathodic protection, these coatings typically contain a high proportion of metallic zinc particles, often exceeding 90% by weight in the dry film. The zinc particles function as sacrificial anodes, preferentially corroding to shield the underlying steel from oxidative damage (Cui et al., 2014).

Research has shown that incorporating conductive fillers, such as graphene and iron oxide nanoparticles, can enhance electrical connectivity among zinc particles, even when the PVC content is reduced. This enhanced connectivity improves cathodic protection effi-

ciency and improves coating mechanical properties (Li et al., 2021).

Beyond offering cathodic protection, CGC also improves corrosion resistance by promoting the development of passive films. As zinc particles oxidize, they produce corrosion products—primarily zinc hydroxide and zinc carbonate—which subsequently precipitate to form a protective layer on the steel surface. This barrier impedes the ingress of corrosive agents, thereby enhancing the overall effectiveness of the coating system (Guo et al., 2021). CGC also offers practical advantages over traditional HDG, particularly in scenarios requiring in-situ repairs or for complex structures where disassembly is not feasible. These coatings can be applied using conventional techniques, such as brushing, rolling, or spraying, thereby eliminating the need for high-temperature processes characteristic of HDG (Muster and Cole, 2004).

Recent research has highlighted significant improvements in corrosion protection that CGC offers through several innovative strategies. For example, incorporating graphene and iron oxide nanoparticles into CGC has enhanced their cathodic and barrier performance. These nanoparticles effectively occupy the gaps between zinc particles, thereby reducing porosity and increasing the coating's density—an essential factor in preventing the penetration of corrosive agents (Cui et al., 2014). Furthermore, the development of dual protection systems that combine cold galvanizing with powder coatings has achieved high corrosion resistance classifications (C4 and C5) in accordance with DIN EN ISO 12944 standards. This method presents a more energy-efficient alternative to conventional HDG, especially for complex structural components. Additionally, surface modification techniques, such as nitriding of zinc-coated steel substrates, have been utilized to improve the longevity of CGC. Specifically, annealing in an ammonia atmosphere forms a hardened surface layer that enhances wear resistance, adhesion strength, and corrosion resistance across diverse environments (Petrova et al., 2010). Furthermore, CGC outperforms electroplated zinc coatings in saline and soil environments, offering more stable dissolution behavior without requiring environmentally hazardous post-treatments (Qin et al., 2023).

4.2.1 Process of Galvanizing

ZRP is commonly applied to steel substrates that have been surface-prepared through sandblasting, utilizing techniques such as brushing or spraying. These primers, formulated with either organic or inorganic binders, are typically applied to achieve a dry film thickness ranging from 2.5 to 3.5 mils, particularly in touch-up or repair operations on HDG steel surfaces. Their widespread adoption is largely due to their prac-

tical applicability in field conditions and compliance with the ASTM A780 standard for the repair of galvanized coatings (Farooq et al., 2021).

Much like conventional paint coatings, zinc-rich primers (ZRP) serve as surface layers that form a mechanical bond with the steel substrate, typically exhibiting adhesion strengths in the range of several hundred pounds per square inch (psi). ZRPs are generally categorized into two types: organic, comprising materials such as epoxies, chlorinated hydrocarbons, and other polymers, and inorganic, which are primarily formulated with alkyl silicates. Both variants are commonly applied to achieve a dry film thickness of approximately 2.5 to 3.5 mils (64–90 μm) (Thierry et al., 2018).

A key feature common to all zinc coatings is the ability to provide cathodic protection. However, ZRP coatings differ from others due to the inclusion of a binding material to adhere particles to the surface. To achieve effective cathodic protection, the concentration of zinc dust within the coating must be adequately high to maintain continuous electrical conductivity between the zinc particles and the underlying steel substrate. This requirement emphasizes the importance of maintaining constant agitation and achieving a homogeneous mixture during application. However, some uncertainty remains regarding the feasibility of cathodic protection when particles are fully encapsulated within a non-conductive binder (Spennemann, 2021).

The performance characteristics of organic zinc-rich primers (ZRP) are largely influenced by the solvent system used in their formulation. However, organic ZRPs exhibit lower thermal resistance, generally limited to 422K, compared to their inorganic counterparts. Additionally, they are more susceptible to degradation from ultraviolet (UV) exposure and generally offer inferior corrosion resistance relative to inorganic zinc-rich coatings (Farooq et al., 2021).

4.2.2 Corrosion and Efficiency Rate of Cold Galvanizing as Corrosion Protection

Several experiments conducted in recent years have been correlated with the exposure of steel specimens to atmospheric corrosion with cold galvanizing protection, as presented in Table 3.

Collectively, cold galvanizing protection provides a reduction, resulting in excellent efficiency compared to structural steel elements without any protective coating. This is also consistent with HDG coating, where the zinc coating method applied to the surface of structural elements with varying thicknesses protects the structural and mechanical elements of steel structures. The corrosion process on the zinc layer, as shown in Figure 5, confirms that the cold galvanizing protective

layer protects atmospheric environments through environmental variables and surrounding pollutants.

4.2.3 Corrosion Mechanism of Cold Galvanizing

The corrosion product composition has been investigated in several studies (Zhang, 1996; Leygraf et al., 2016). Field exposure commonly results in the formation of basic zinc salts, which contain anions such as carbonate, chloride, and sulfate. Zinc oxide is frequently identified among the products, with zinc hydroxide also being occasionally reported. In addition to these basic salts, nonbasic zinc compounds—such as zinc carbonate (ZnCO_3) and hydrated zinc sulfate ($\text{ZnSO}_4 \cdot n\text{H}_2\text{O}$)—have likewise been identified. The formation of corrosion products varies across different environments, primarily influenced by the relative concentrations of chloride and sulfur-containing pollutants in the atmosphere (Lide et al., 2003; Veleva and Kane, 2003). Due to the structural similarities among zinc hydroxycarbonate, hydroxychloride, hydroxysulfate, and hydroxyl chlorosulfate compounds, it is reasonable to infer that transformations between these phases may occur under favorable environmental conditions.

For instance, specific formation pathways have been proposed under sheltered conditions, particularly in atmospheres characterized by high sulfur dioxide (SO_2) pollution and relatively low concentrations of other contaminants.

Table 4 illustrates the corrosion resistance of ZRP-coated steel, demonstrating that the zinc-rich surface layer significantly reduces corrosion rates in atmospheric conditions. Experiments conducted by Priyotomo et al. (2020) during 200 days of exposure in coastal marine environments showed that galvanized steel exhibited approximately 20% greater corrosion resistance than ungalvanized steel. This finding is consistent with the results from Anyiam et al. (2020), Tjahjanti et al. (2022), Natesan et al. (2006), and Shiri and Rezakhani (2020), which collectively indicate that the efficiency rate of galvanizing steel varies depending on the comparison with ungalvanized steel.

5 CORROSION PROTECTION EVALUATION

Corrosion protection is provided by a coating or protective layer on the metal surface, which prevents the formation of corrosion products and protects the metal surface even after some initial deterioration. To ensure effective performance, it is essential to evaluate their efficiency and determine whether system adjustments are necessary. Several methodologies are available for assessing the performance of both synthetic and natural corrosion protection systems (Lowmunkhong et al., 2010).

Table 4. Corrosion and Efficiency Rate of Cold Galvanizing Protection

Case	Protection	Location (Aggressiveness)	Exposure Time (year)	Corrosion Rate (mm/year)	Efficiency Rate (%)	References
1	Galvanized with Zn surface layer ±98% purity No protection	Atmospheric Corrosion (C5)	5/365	8.300 15.500	1.867	Anyiam et al. (2020)
2	Galvanized with Zn surface layer ±85-100% purity No protection	Atmospheric Corrosion	200/365	0.100 2.000	20.000	Priyotomo et al. (2020)
3	Galvanized with Zn surface layer 85% purity No protection	Atmospheric Corrosion	0.4/365	0.260 0.830	3.192	Tjahjanti et al. (2022)
4	Galvanized with Zn surface layer ±99.9% purity No protection	Atmospheric Corrosion (C4)	5	0.007 0.524	74.857	Natesan et al. (2006)
5	Galvanized with Zn surface layer ±90% purity No protection	Atmospheric Corrosion (C4)	1	2.250 10.360	4.604	Shiri and Rezakhani (2020)

5.1 The Weight Loss of Specimens

The specimens at varying concentrations were pre-cleaned, dried, and weighed to assess material loss. Weight loss measurements were systematically performed, and the average values were recorded. The corrosion rate (v_{corr}) was then determined following the standardized methodology outlined in the ASTM G1 standard (ASTM, 2011).

$$v_{corr} = \frac{K \cdot W}{A \cdot T \cdot D} \quad (4)$$

Where K is the constant number, W is the weight loss of the specimen (g), A is area in cm^2 , T is time of exposure (hour), and D is density (g/cm^3)

5.2 Classification and Estimation of the Corrosion of Metals in the Atmospheric Environment

This framework defines corrosivity categories for atmospheric environments based on the first-year corrosion rates of standard specimens. It provides a dose-response function to enable normative estimation of corrosivity categories by calculating the corrosion losses of standard metals during the initial year of exposure. Additionally, it facilitates an informed assessment of corrosivity levels based on local environmental conditions.

The classification of corrosivity categories and levels refers to the standard of ISO 9223 (ISO, 1992), which classifies environments by aggressiveness level: (very

low), C2 (low), C3 (medium), C4 (high), C5 (very high), and CX (extreme), each indicating an increasing severity of environmental exposure in relation to metal type.

5.3 Corrosion Protection Effect On the Rate and Efficiency

The performance of organic corrosion protection is often quantitatively assessed using the weight loss method, a widely recognized approach valued for its simplicity, reliability, and effectiveness in evaluating corrosion behavior. Experimental data derived from weight loss measurements of mild steel immersed in acidic environments at varying temperatures and protection concentrations reveal a consistent pattern: as the protection concentration increases, the inhibition efficiency (η_w) improves, while the corresponding corrosion rate (v_{corr}) declines. This inverse relationship is attributed to the greater adsorption of protection molecules onto the steel surface at higher concentrations, resulting in a more robust protective film that impedes corrosive attack (Mahdi et al., 2022). The reduction in η_w with increasing temperature is more evident at lower protection concentrations. The high-temperature-dependent decline in η_w becomes less significant, suggesting that sufficient protection coverage can mitigate the thermal effects on corrosion protection (Nishikata et al., 1995).

Tables 3 and 4, which present the efficiency results of HDG or cold galvanizing protection on structural steel elements, provide an overview indicating that protection can occur through several parameters. The zinc

coating on the surface of structural steel elements can slow down the corrosion rate, which impacts efficiency through the low corrosion rate value produced compared to elements without protective coatings. The thickness and method of zinc coating also influence the corrosion rate and efficiency, resulting in different values for HDG and cold galvanizing.

6 EXPERIMENTAL STUDIES OF CORROSION ON GALVANIZED STEEL

6.1 Hot-dip Galvanizing Provides Protective Layers Against Atmospheric Corrosion

Experimental evidence on galvanized coatings exposed to atmospheric conditions reveals significant variations across studies. Referring to Table 3, for instance, Vera et al. (2013) reported that HDG steel with an 80 μm coating exposed for 1.25 years in a C5 (very high level of aggressiveness) environment exhibited only about 2% efficiency, highlighting the vulnerability of galvanized layers in chloride-rich conditions. In contrast, multi-site investigations in Chile and Mexico by Del Angel et al. (2015) demonstrated that despite the presence of SO_2 and Cl^- pollutants, the corrosion rate of HDG steel declined as average temperature increased, suggesting a possible mitigating role of climate change-driven warming. Further evidence from Vera et al. (2019) and Vera et al. (2023) indicated that 85 μm HDG coatings maintained efficiency rates of approximately 25.42% and 25.95% after three years in CX (extreme) environments, though performance varied depending on local site parameters.

As a result, corrosion rates of HDG steel at each test site exhibited a declining trend with increasing average temperatures, irrespective of ambient pollutant concentrations. Based on the tests conducted, it can be seen that using HDG as a steel protection method is highly effective in suppressing various pollutant variables associated with atmospheric corrosion. Correlated with Zhang (1996) and Leygraf et al. (2016), the effectiveness of HDG is attributed to the presence of a zinc layer that protects the steel surface, thereby preventing damage to the main elements of the material.

6.2 Cold Galvanizing Protective Layers for Atmospheric Corrosion

Referring to Table 4, the evidence on Cold-Galvanized Coatings (CGC) under atmospheric exposure reveals significant variations across studies. Some studies on cold galvanizing coatings (CGC) have consistently demonstrated higher apparent protection efficiencies. Priyotomo et al. (2020), for example, observed that galvanized steel coated with zinc-rich paint (85–100% Zn) corroded 20 times slower than carbon steel dur-

ing a 200-day exposure in coastal Indonesia, yielding efficiency values around 200%. Similarly, Tjahjanti et al. (2022) reported that 85% Zn CGC applied in a C4 (high level of aggressiveness) environment achieved over 200% efficiency within 0.4 years of testing.

A key factor influencing the corrosion rate is the distance between the test site and the coastline, with sites closer to the coast experiencing increased corrosion due to greater exposure to corrosive environmental conditions.

7 CHALLENGES AND LIMITATIONS OF GALVANIZED STEEL AS CORROSION PROTECTION

Galvanized steel is widely employed in various industries as a cost-effective and reliable method of protecting steel structures against atmospheric corrosion. However, despite its advantages, galvanized steel presents several limitations that constrain its long-term effectiveness, particularly under certain environmental and mechanical conditions (Al-Baghdadi and Alamiery, 2025). One of the multidirectional box-shaped shearing damper tests conducted with metallic materials by Setiawan et al. (2025) was proposed to reduce seismic forces in a bridge structure. However, using a metallic damper for a bridge located in a high-corrosion potential zone presents a significant challenge. This requires early analysis and prevention of potential corrosion on the metallic damper by using the appropriate metal material. Based on this, a galvanized protective layer has the potential to be implemented for metallic dampers in bridge structures.

The processing and environmental constraints, such as acid bath effluents, zinc-rich wastes, and uneven coverage on oversized or intricate geometries, pose both technical and ecological challenges (Baltazar-Zamora et al., 2019). Microcracking under thermal shock, coating delamination above 200°C, and localized degradation near welded zones significantly reduce service life (Liu et al., 2022). The limitations in soil and submerged applications are pronounced; the accumulation of zinc corrosion products in marine embedded structures may accelerate steel deterioration rather than inhibit it (Pereira et al., 2015). Moreover, the geographic bias toward temperate regions leaves tropical or equatorial conditions, where corrosion rates are often accelerated, largely underrepresented (Abid et al., 2022).

8 RECOMMENDATION

Corrosion protection is important in preventing metals and alloys from deteriorating in various sectors. Some possible future advancements may advance the field:

1. Predictive Modeling

Integrating artificial intelligence, such as Artificial Neural Networks and Fuzzy Logic for corrosion rate prediction, should be further advanced, as initial studies have already demonstrated their potential in modeling atmospheric degradation processes (Mahdi et al., 2022). This strategy directly addresses the limitations of conventional exposure testing, which typically requires one year or more.

2. Standardized Field Experiments

Context-specific testing in tropical and coastal environments is urgently needed. Current data are skewed toward temperate climates, which may underestimate the severity of corrosion in high-humidity, chloride-rich conditions typical of Southeast Asia. Field validation in tropical climates remains limited, necessitating new datasets that simultaneously capture the influence of chloride, SO₂, and time of wetness (TOW).

3. Integrated Protection Strategies

Combining HDG and CGC with advanced coatings offers a hybrid pathway, delivering immediate cathodic protection and enhanced barrier performance. Such dual systems could mitigate many weaknesses observed in stand-alone HDG or CGC applications. Additionally, hybrid protection strategies that combine HDG with graphene-modified zinc-rich primers, as proposed by Abid et al. (2022), represent a promising research frontier, offering both enhanced cathodic protection and superior barrier performance.

9 CONCLUSION

This review systematically evaluated the performance of galvanized steel under various atmospheric conditions, integrating findings from recent studies on both Hot-Dip Galvanizing (HDG) and Cold Galvanizing Coating (CGC) methods. Overall, the comparative assessment demonstrates that zinc-based coatings remain one of the most effective and practical methods for protecting steel against corrosion in industrial and marine environments.

The efficiency values were obtained by comparing galvanized steel elements with carbon steel without protective coatings in an atmospheric environment and are obtained in galvanized steel due to the effectiveness of the zinc layer on the surface through various methods, which protect the atmospheric environment, where some elements such as Temperature, Relative Humidity (RH), Time of Wetness (TOW), and pollutants contribute to the aggressiveness of corrosion rates. Based on the influence on the atmospheric environment, aggressiveness is certainly the most important factor in determining the rate of corrosion. In the HDG protection, the highest corrosion rate efficiency value of 25.95% was obtained through expo-

sure to an extreme environment (CX) or a combination of environmental conditions that produced the highest corrosion rate values in corrosivity categories. In contrast, CGC variation yields the highest corrosion rate efficiency value of 74.857%, obtained under an atmospheric environment with high aggressiveness (C4). The corrosion rate values obtained need to be based on the conditions and effects of the exposure environment to produce a more accurate corrosion rate effectiveness value.

Through a critical analysis of contemporary research efforts, methodologies, and prevailing challenges, experimental studies have shown that HDG and CGC significantly enhance corrosion resistance under atmospheric conditions, regardless of exposure levels within the area. This can be an innovative strategy and a forward-looking approach to addressing corrosion issues in various industrial sectors and applications.

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