

A Review of Nanoparticle Coating with Galvanized Steel and Industrially Significant Zinc Corrosion Inhibitors

Saraswati Kumari Ola¹, Ishita Chopra¹, Priyanka Choudhary¹, Veena Dhayal¹, Triveni Ola², and Anand Kumar¹

¹Department of Chemistry, Manipal University Jaipur, Jaipur, Rajasthan, India

²Department of Chemistry, Smt. Indramani Mandelia Shiksha Niket, Pilani, Rajasthan, India

*Correspondence to:

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Abstract

Recently, tremendous interest has been devoted to zinc as an important metal in the semiconducting industry due to their electrical and optical properties. Zinc's principal applications are galvanization and as an anode in batteries. Galvanized steel, which is steel coated with zinc, is frequently used in industries. Even while zinc shields many metals from corrosion, it itself corrodes in a variety of acidic and neutral situations. Zinc's corrosive behaviour is relevant in all sectors where it is used directly or indirectly as a protective coating. Many inhibitors may be combined to form good inhibitors with an inhibition effectiveness of 80 – 90%. This study summarizes three decades of research on corrosion and inhibition investigations of zinc and galvanized steel.

Keywords

Nanoparticle, Corrosion, Zinc, Inhibitors, Galvanized steel

Introduction

Corrosion is the inevitable decomposition of metals and alloys as a result of their interactions with the environment [1]. Despite the fact that ferrous materials have been known to corrode spontaneously in a variety of acidic and alkaline environments, corrosion of nonferrous substances is not a novel phenomenon. There are several papers on corrosion of nonferrous materials like aluminium and its alloys, zinc, and some other materials in the literature. Other metals, primarily steel, are routinely coated with zinc. Zinc will corrode severely if the pH is less than 6 and more than 12 [2].

Pickling, descaling, and other industrial operations include the treatment of metals with acids. Zinc is prone to severe corrosion as a result of these processes [3]. Corrosion in maritime settings is caused by the interaction of metal surfaces with marine aerosols that have fallen on them [4]. In addition, zinc is susceptible to air corrosion. Corrosion prevention, both direct and indirect, helps to decrease a variety of problems [5]. As a result, material researchers and corrosion experts want to reduce the impact of corrosion on people from all walks of life in a variety of scenarios [6].

As a result, economic losses would be reduced, and industrial safety would be improved, ultimately protecting and preserving technical materials. Despite the fact that researchers have concentrated on corrosion inhibition studies using a variety of methodologies, corrosion inhibitors have been supported as the key instrument for slowing the rate of corrosion [7]. Organic inhibitors are heterocyclic molecules with the heteroatoms O, N, S, and P.

These heteroatoms have a lone pair of electrons and are high electron density centres. They create a covalent/coordination connection with metal rapidly [8]

through these reactive sites. As a result, they prefer to deposit a protective layer on the surface of the metal. It will act as a barrier between the metal and the corrosive, preventing the metal from dissolving and therefore material loss [9].

Corrosion inhibitors are a cost-effective and adaptable method of preventing corrosion. In the industrial sectors, they are solely used in a variety of ways. In the oil extraction, processing, and chemical industries, they are utilised as a first-line protection [10]. Metal damage is minimised, hydrogen embrittlement is reduced, and the metal is protected using these inhibitors. They manage anodic, cathodic, or both reactions to prevent corrosion. Every year in industries, several organic compounds are created and assessed for anti-corrosion performance in various industries related to engineering in various media [11].

Coatings, cathodic and anodic protection, and material selection are among the various approaches used at the industrial level [12]. This is a part of research related to corrosion behaviour and inhibition of nonferrous materials under dynamic and static conditions [13]. In this present review paper, an overview of zinc corrosion inhibition techniques in various corrosive media was involved and green inhibitors were used for the environmental related issues and leads to the good efficiency and helps in corrosion protection.

Corrosion Control Requires Green Inhibitors

Multiple bonds and heteroatoms in synthetic substances are efficient inhibitors. Organic inhibitors, on the other hand, are said to be either expensive or poisonous. Toxicity might occur during the preparation or application process [14]. The inhibitor's toxicity can sometimes have negative consequences for humans or the environment. Furthermore, some inorganic chemicals, such as chromates, have been shown to have excellent anticorrosive properties, but are exceedingly harmful to both humans and the environment [15].

The protection of the environment and human health should be a top priority. There is a constant push to replace harmful inhibitors with environmentally benign inhibitors [16]. Over the last decade, research has shifted its attention to ecologically benign, environmentally friendly inhibitors. Green inhibitors are what they're called. Green corrosion inhibitors are non-toxic materials that are free of heavy metals and other hazardous substances. Because of their adsorptive capabilities, they are called as homepage elements or adsorption site blockers. Green inhibitors, often known as "eco-friendly inhibitors," are chemicals that are biocompatible with the natural environment [17]. In addition, research into the use of natural materials such essential oils, plant extracts, biopolymers, and surfactants as ecologically acceptable corrosion inhibitors is expanding. Plant materials have been reported as proper and effective corrosion inhibitors among various types of green inhibitors [17].

Plant extracts are considered biologically derived green inhibitors. They have gradually replaced synthetic organic and inorganic inhibitors in recent decades [18]. The tannins,

alkaloids, flavonoids, and other organic compounds present in these extracts are abundant. Agriculture is unique to each tropical location and agricultural waste creates tons of rubbish. The bio-waste material left behind from the usage of nutritional compounds will function as effective inhibitors for metal surface protection [19]. Corrosion inhibitors may be made from them at a very low cost. Only a few examples are solid waste from sugarcane, banana and watermelon cores, glycolipids, watermelon rind, rice husks, peel, seeds, tomato peel waste, generated from pineapple waste, sunflower oil cakes, and *Phoenix dactylifera* seeds [20].

The effective utilisation and extracting of phytochemicals from such sites do not need a large investment and the task may be completed at a minimal price with excellent inhibition efficiency [21]. Plant extracts are thus effective green inhibitors with both economic advantages. There are non-hazardous behaviour reports available for a number of plant product uses in industries [22].

Use of *P. dactylifera* seeds as a steel corrosion inhibitor, lettuce blossom stalks and sweet potato stems are only a few examples. Because the majority of the plant materials utilised exhibited promising inhibitory efficiency, they were an efficient tool for material conservation. There is no comprehensive literature on the use of plant products as zinc corrosion inhibitors, despite the existence of a few review papers on using plant products as corrosion inhibitors for stainless steel, aluminium, mild steel, and its alloys [23].

Zinc, being a nonferrous metal, has a diverse variety of uses [24]. This concise study describes the use of plant products to prevent zinc corrosion in a variety of alkaline, acidic, and neutral environments. This allows material scientists and corrosion engineers to quickly access prior literature, as well as its substance and contemporary changes, all of which contribute to sustainable and green production in Figure 1 [25].

Zinc Corrosion Behaviour

Zinc corrodes rapidly at pH levels below 6 and above 12. It corrodes slowly at pH levels between 6 and 12. Acid corrosion is a serious problem for zinc. Descaling, cleaning pickling the metal surface all need acids. Metals must be cleaned with dilute mineral acids before they can be utilised in applications in all sectors. Zinc corrosion and inhibition

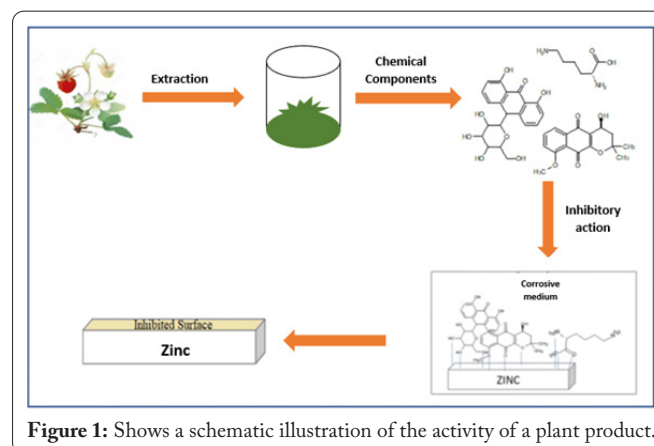


Figure 1: Shows a schematic illustration of the activity of a plant product.

investigations in various acid media, such as hydrochloric acid (HCl) have been widely investigated [26]. Zinc dissolves slowly in alkaline liquids, producing zincate ions and releasing hydrogen. Zinc has been tested with a variety of electrolytes, including sodium hydroxide and potassium hydroxide. Zinc oxide, zinc hydroxide and zinc hydroxide carbonate are all corrosion products that can be formed by alkaline media [27].

Oxygen, moisture, and salt, mainly sodium chloride (NaCl), all degrade metal faster than rust. All of these corrode the metal by eroding it, weakening it, and which causes it to crumble. The metal is corroded as a result of saltwater damage. Many ways have been used for effective corrosion avoidance in salt water [28].

Organic Inhibitors to Prevent Zinc Corrosion

Heteroatoms are common in organic inhibitors. Higher basicity and electron-donor abilities are found in O, N, S, and P, which operate as corrosion inhibitors. The active sites for the adsorption process on the surface of metal are O, N, S, and P. Inhibitors are one of the most efficient ways to protect metals against corrosion [29]. These inhibitors form a hydrophobic coating which protects adsorbed molecule on the metal surface, preventing the metal from dissolving in the electrolyte. Several authors have recently reported that synthetic organic compounds like ethoxylated fatty acids, ammonium compounds, m-substituted aniline-N-salicylidene, ethylenediamine N, organic phosphonium, N'-di (p-methoxybenzylidene), ziprasidone, semicarbazide, and 2-[4-(methylthio) phenyl] inhibit zinc corrosion [30].

Zinc corrosion inhibitors for acidic environments

In an acidic atmosphere, zinc is susceptible to corrosion. As a result, dilute mineral acids are commonly used for pickling and descaling. The primary cathodic reaction in a highly acidic media causes zinc to corrode more quickly. The additional inhibitor, on the other hand, performs a critical function by being adsorbed on the metal surface, slowing hydrogen development and safeguarding the metal surface [31].

The corrosion performance of zinc and its suppression in an acidic environment have been extensively studied by several

researchers for metal pickling, HCl is widely suggested [32]. Despite the fact that the acid's primary function is to remove foreign elements from the material's surface, it dissolves the materials to a large level due to its aggressive character, even if it is dilute. As a result, inhibitors are frequently added to acidic solutions in order to slow metal breakdown. The effectiveness of the inhibitor is determined by its electrolyte composition, structure, and charge on the metal surface [33]. Inhibitors have been shown to work with a wide range of chemical substances. Many scientists have looked at the dissolving of zinc in HCl using various chemical inhibitors. Some well-known medicines with active functional groups, including as, spectinomycin, streptomycin, paromomycin, ketosulfone, ziprasidone, and seroquel [33] were effective inhibitors of zinc corrosion in HCl. Their capacity to inhibit is solely owing to the presence of nonbonding electrons, as well as heterocyclic rings. Sulphuric acid (H₂SO₄) is used to clean condensers and cooling towers of rust, algae, and scale [34,35]. Because nitric acid (HNO₃) is a powerful oxidizer, it destroys almost all metals. Despite its mildness, phosphoric acid (H₃PO₄) has been shown to corrode metal substantially. Sulfamic acid is a powerful acid that is used to clear cooling towers and condensers of rust, algae, and hard water scale [35]. Anticorrosive substances such as organic phosphonium and ammonium compounds have been explored and evaluated for zinc corrosion in 1.0 M H₃PO₄. Also tested for corrosion inhibition of zinc in HNO₃ were isomers of toluidine in sulfamic acid and HNO₃ and ethylamine. Table 1, Some inhibitors showed moderate to good efficiency of about more than 85%, with a few exceptions. [36]

Zinc corrosion inhibitors in neutral environment

Chloride medium is used to study corrosion in maritime settings. As a result, 3.5 percent NaCl solutions are frequently employed to induce experimental circumstances and conduct corrosion tests. Cathodic reaction was primarily stifled by the inhibitor [44]. The creation of a protected organometallic surface on zinc was caused by zinc chelation with organic molecules. Another research used Benzaldehyde thiosemicarbazone as an inhibitor in an aqueous chloride-sulfate media. A strong adhering layer generated on the metal surface due to extremely electronegative sulfur atoms and nitrogen. Aramaki used several anionic and cationic inhibitors to study zinc corrosion in NaCl. The use of cationic inhibitors

Table 1: Zinc corrosion inhibitors for acidic environments.

Inhibitor	Medium	Method	Inhibitor type	Efficiency (%)	References
Aniline (C ₆ H ₅ NH ₂)	0.01, 0.5, and 0.10 M HCl	Weight loss, potentiodynamic polarization (PDP)	Mixed	94	[37]
Triethylamine (C ₆ H ₁₅ N)	0.05 M HCl	Weight loss, PDP	Mixed	96	[38]
Ketosulfone	0.1 M HCl	PDP, EIS	Mixed	59	[49]
Ethylenediamine N,N-dibenzylidene	0.5 M H ₂ SO ₄	Weight loss	Cathodic	99	[40]
Ethoxylated Fatty acids	1.0 M HCl 1.0 M H ₂ SO ₄	PDP, weight loss	Anodic	80	[41]
Organic phosphonium and ammonium compound	1 M H ₃ PO ₄	EIS, PDP	Anodic, and mixed	92	[42]
Toluidines	0.15 M HNO ₃	Weight loss, PDP	Mixed	88	[43]

yielded the best results [45]. The pitting corrosion behaviour of zinc in NaCl, sodium bromide, and sodium iodide was studied [46]. The creation of a protective barrier of zinc oxide at the anodic region resulted in passivity. The aggressiveness of halide ions toward passive film stability reduced in the following order: I < Br < Cl. Zinc corrosion was increased by an increase in halide ion temperature and concentration. Hinton et al. investigated zinc-coated and zinc steel corrosion in tap water with low levels of cerous chloride. The protective layer was created by immersing heated zinc or zinc-coated surfaces in cerous chloride solution for an extended period of time or by quenching them in cerous chloride solution [47].

Table 2 shows the inhibitors utilised in the near-neutral medium. Almost all inhibitors had remarkable inhibition effectiveness, with Ce³⁺ exhibiting the highest inhibition efficiency. This is due to the direct interaction of hydrated Ce³⁺ with solution hydroxide, which results in the creation of a cerium-rich oxide and hydroxide layer.

Techniques of Experimentation

The bulk of the literature said that both classical and electrochemical methodologies were used to study corrosion and inhibition. Weight reduction is one of the most popular and dependable conventional approaches. Many researchers still use it because it produces extremely repeatable findings. This technique, on the other hand, takes time [55]. Nowadays, researchers choose fast electrochemical techniques. The quick potentiodynamic polarization technique provides a wealth of information on corrosion potential, corrosion current density and so on. All of these electrochemical variables help to determine the kind and mechanism of corrosion inhibition [56]. The EIS method contributes to a mechanistic knowledge of inhibition and corrosion. It includes thorough information on the many resistance characteristics that influence the corrosion and inhibition process. It is conceivable to demonstrate that inhibitory efficiency as measured by all three approaches will agree with one another with less than 2% variance based on the meticulous experimental observation [57]. The weight loss method is the most well-known and straightforward corrosion monitoring technique. The method entails exposing a material specimen to a process environment for a set period of time before removing the specimen for analysis. The basic

measurement established by corrosion coupons is weight loss, with the weight loss occurring throughout the duration of exposure given as corrosion rate [58]. Scanning electron microscope was used to study surface morphology, Energy-dispersive X-ray spectroscopy was used to study elemental composition, and Atomic force microscopy was used to study topography in published articles about zinc corrosion inhibition in various media. Infrared (IR) spectroscopy is used to evaluate gaseous molecules' molecular structure/geometry, bond lengths, and bond angles, as well as qualitative and quantitative hydrocarbon analysis on filters, in air, or in water. The IR area is separated into two parts: the group frequency region and the fingerprint region. The group frequency range is 4000 - 1500 cm⁻¹, while the fingerprint region is 1500 - 400 cm⁻¹. Peaks belonging to distinct functional groups may be seen in the group frequency area. The functional group may be established using the associated peaks. Each atom in the molecule is joined by a bond, and each connection needs a different IR area, resulting in distinct peaks. This part of the IR spectrum is known as the molecule's fingerprint. It may be identified by distinctive peaks [59].

Ultraviolet-Visible spectroscopy, also known as ultraviolet-Visible spectrophotometry, is the study of absorption or reflectance spectroscopy in the ultraviolet-visible spectral range. It analyses numerous compounds based on how they absorb light wavelengths, which may then be used to determine what composition they are made of. When a material absorbs light, a colour appears. The colour absorbed is the inverse of the colour that emerges (it absorbs every other wavelength than the one it appears). For example, chlorophyll, the pigment found in green plants, looks green because it absorbs violet and red light rather than green light that is reflected off the molecule [60]

X-ray diffraction spectroscopy (XRD) techniques have been used for the analysis of inorganic pigments and extends by analysing the material's crystalline structure rather than its elemental content: for example, it is typically capable of differentiating the crystalline forms of titanium dioxide, rutile, and anatase. The detector travels in a circle around the sample, recording the number of x-rays at each angle of 2 theta [61]. Surface morphology investigations revealed inhibitor deposition on the metal's surface, establishing a physical barrier between corrosive and metal [62]. After using the inhibitor, the surface has become quite even. The elemental composition on

Table 2: Shows zinc corrosion inhibitors in a neutral media.

Inhibitors	Medium	Maximum IE%	Method	References
Zinc Phosphate	3.5% NaCl solution	96	Electrochemical	[48]
Benzimidazole	3.5% NaCl solution	74.0	Electrochemical	[49]
N-phenylaminopropoxy-N.N.N-triphenyl propane-1.3-diamine	1M HCl	79.3	Electrochemical	[50]
Benzaldehyde thiosemicarbazone	Aqueous chloride-sulfate	87	Galvanostatic polarisation	[51]
Ce(NO ₃) ₃ ·6H ₂ O	0.5 M NaCl	91	Potentiodynamic polarization method, Weight loss	[52]
La ³⁺ , Al ³⁺ , Ce ³⁺ , Ce ⁴⁺	0.5 M NaCl, NaBr, NaI	93	Cyclic voltammetry, PDP	[53]
2-Hydrazono-3-bornanemethylenedithiol disodium salt	0.2 M Na ₂ SO ₄ + 0.2 M NaCl, pH 6	90	EIS, polarisation measurements	[54]

the metal surface was studied using Energy-dispersive X-ray spectroscopy. In virtually every case, the percent composition of components responsible for barrier film production increased. This confirms inhibitor adsorption on metal surfaces. Spectroscopic methods and quantum chemical computations, on the other hand, can be used to further investigate and enhance [63].

Galvanized steel corrosion studies

Galvanization is the process of coating iron or steel with zinc. Zinc acts as a sacrificial anode to preserve the underlying metal in galvanized products. Zinc, being a lower noble metal, will corrode, shielding the base metal. Electrodeposition, thermal spraying, and hot dip galvanization are the most common coating methods. Galvanized steel pipes are used extensively in industry. Galvanized steel cables are used in communications cables, earth wires, and suspension bridges, as well as in fence to support wall projects, closing shutting windows, and as a building material. Galvanized steel sheets are used in house railings, frames, playground equipment, reinforcing beams, street furniture, nails, bolts and nuts, pipelines, and cars. Architectural elements, concrete reinforcing, maritime and coastal projects, and transport system all employ galvanized steel bars [64]. Cooling towers, conveyor castings, supports, agricultural tools, condensers, etc. are all examples of industrial applications.

When the Zn surface of galvanized steel buildings becomes moist from rain, mist or dew, atmospheric corrosion begins. According to a report published in the United States, atmospheric zinc corrosion is worse in seawater [65]. Reinforced concrete is a common building material. Steel corrosion and concrete spalling are greatly reduced with hot-dip galvanized reinforcement. As a result, it has a consistent and expense impact on concrete strength. Even though galvanized steels are relatively corrosion-resistant, they do corrode under specific circumstances and in particular media [66]. Galvanized steel corrosion in pH 2 – 4 and 8 – 10 solutions with a low sodium chloride content (0.05 – 1 M) at 25 – 55 °C. Zinc corrosion products were easily soluble in water in a pure acid media. Water-soluble products were generated in strong alkaline solutions [67] This expedited the corrosion process by exposing steel that needed to be protected as well as eroding the corroded protective layer on the galvanized steel surface. Because the exposed steel remained cathodically shielded by zinc after zinc, the corrosion rate of zinc dropped considerably with rising temperature, particularly in alkaline conditions. Galvanized [68] steel wire corrosion in a NaCl-containing humid environment. The rate of corrosion rose dramatically as salt content increased, especially at high temperatures. Furthermore, at humidity levels lower than 60%, this item did not corrode. Investigated the behaviour of galvanized corrugated reinforcement bars meant to simulate aquatic conditions in concrete pores [69]. In the presence of potassium hydroxide and sodium hydroxide a white, powdery corrosion product was seen. Furthermore, hydrogen evolution was detected at pH levels higher than the 12.80.1 threshold. Using calcium hydroxide solutions, galvanized [70] bar corrosion in the pH range of 11.1 – 12.6. pH of solution and corrosion products

$\text{Ca}(\text{Zn}(\text{OH})_3)_2 \cdot 2\text{H}_2\text{O}$ had an impact on corrosion kinetics. At pH 11.5 there was limited corrosion. In the presence of six different inhibitors, corrosion barrier of HDG steel panels in NaCl solution. 5.8 – 6.3 pH. The highest corrosion protection was provided by $\text{Ce}(\text{NO}_3)_3$, whereas $\text{Ca}_3(\text{PO}_4)_2$ had no effect [71]. 1,8-diazabicyclo[5.4.0]undec-7-ene as a galvanized steel inhibitor in hydrogen chloride at 30 and 40 °C. At 30 °C, DBU had an 88% inhibitory effectiveness. In 0.05 M NaCl, the corrosion resistance of hot-dipped galvanized steel. On an HDG substrate, mechanically scratched material, the efficacy of Na_2MoO_4 was assessed. On scratched HDG samples, SVET was used to investigate localized corrosion [72].

Galvanized steel coating studies

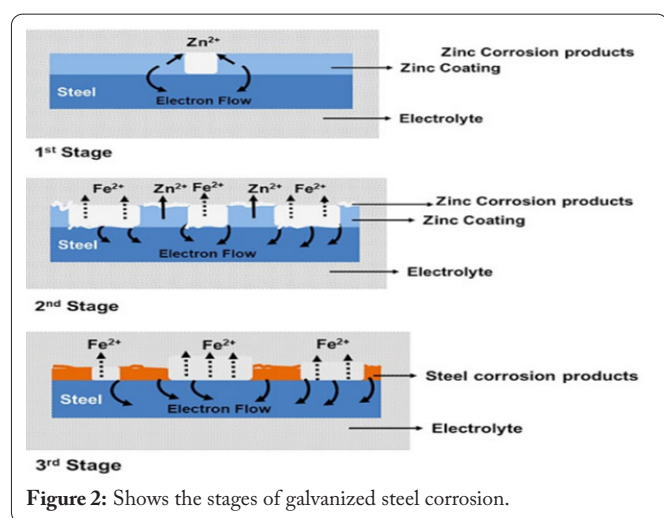
As previously stated, galvanised goods are prone to air corrosion, which could be enhanced by smearing. To prevent corrosion and enhance coating adhesions, galvanised steel sheets should be surface coated with a layer [73]. It's known as coated galvanised steel. This method combines the advantage of organic and inorganic elements. The organic component increases polymer coating compatibility by reducing flaws and increasing flexibility. The inorganic component, on the other hand, is more likely to attach to the metal surface. Lower temperatures can also be used to apply coatings [74]. Acid rain is a combination of sulfuric acid, hydrogen chloride, and nitric acid, which rapidly react with calcium hydroxide to generate an equal quantity of hydrated salts. Because of their increased solubility, they can permeate the internal cracks of concrete. When rainwater evaporates, these salts solidify, producing stress on the metallic structure and eventually failure. As per studies the United States alone invests more than \$5 billion repairing concrete structures damaged by acid rain [75].

Galvanized steel corrosion in artificially acid rain using a mixture of zinc calcium and molybdate/phosphate ion interchange silica. When compared to the colours employed alone, they had a significant synergetic anti-corrosion effect. In simulated acid rain, the corrosion activity of pure zinc, 5% Al-Zn, and 55% Al-Zn film specimens [76]. Steels showed sacrificial corrosion hindrance when galvanized. Zinc alloying and the use of an inorganic silicon sealer improved anticorrosion performance. The inhibitory activity of phosphate and calcium pigments on zinc metal as an alternative for hazardous chromate pigments [77]. The corrosion tests were conducted in an acid rain environment. The pigment mixture created a phosphate coating on the metal, delaying the onset of corrosion. Painted galvanized steel with an epoxy polyamide primer. Coating thicknesses of 100, 200, and 500 micrometres were used. Painted coupons were exposed to a 3% NaCl solution in a horizontal fat cell for corrosion testing [78]. The thinnest primer coating could not provide adequate protection for the metal and it corroded. The efficiency of primer protection, on the other hand, increased with its thickness. Coating strategies to prevent electrolyte or air from entering the metal surface and generating progressive corrosion are the most frequent corrosion mitigation options. As a result, the majority of the work is being directed toward replacing hazardous chromate coatings with safe, non-toxic, ecologically friendly replacements, and numerous coating formulae are now being devel-

oped [79].

Nanoparticle coating studies with zinc and galvanized steel

The anticorrosive qualities of galvanized steel coatings might be improved by incorporating nanoparticles into the coating in Figure 2. Because nanostructured materials have a large effective surface area, they offer remarkable mechanical, electrical, and physicochemical characteristics. These characteristics have prompted researchers to develop coatings with higher wear and wear resistance. The corrosion of hot-dip galvanized steel that had been pre-treated with silicon dioxide (SiO_2) microparticles. Pre-treatment was done using bis[1,2-(triethoxysilyl)ethane silane or bis-(triethoxysilylpropyl]



tetrasulfide [80].

The results revealed that pre-treated silane films infused with silica particles provided the best corrosion protection. The electrochemical performance of galvanized steel that had been pre-treated with bis-(triethoxysilylpropyl) tetrasulfide silane solutions and integrated with SiO_2 or cerium oxide (CeO_2) nanoparticles activated by cerium ions [81]. Silanes created a hybrid compact and homogenous surface coating, which served as a deferral for the onset of corrosion. Furthermore, the presence of nanoparticles strengthened the barrier qualities of the silane coatings and reduced corrosion activity. CeO_2 nanoparticles predominated over SiO_2 nanoparticles [82]. Silane sol-gel films might replace standard chromate pre-treatments. Montmorillonite clay was reformatted to produce Ce(III) montmorillonite clay. The amount of accumulated Ce is taken into account in XRF studies (III). According to XRD, the Ce(III) was discovered in interlayer zones. The influence of ionic counterion and strength type on the kinetics of Ce(III) release in NaCl and zinc chloride solutions was examined [83]. The morphology and electrochemistry of hot-dip galvanized steel treated with 3-glycidoxypropyl trimethoxysilane and bisphenol-A before being impregnated with cerium ion-activated CeO_2 nanoparticles [84]. On coating, the results showed the creation of a rather nanostructured, smooth surface with minimal heterogeneity. Furthermore, nanoparticles have been demonstrated to improve the barrier characteristics of silane coatings, lessening corrosion activities [85]. The corrosion resistance of coriander seed extract in 0.5 M HCl

by incorporating zinc oxide nanoparticles for zinc corrosion. Polarization data demonstrated that these inhibitors worked as combined molecules. The inclusion of nanoparticles has increased the barrier properties of silane coatings because of crack-free films. Nanoparticles also increased the corrosion resistance of a sol-gel hybrid coating [86].

Conclusions

This review article gives a summary of many chemical inhibitors that are utilised to limit zinc breakdown in alkaline, neutral, and acidic media. A comprehensive review of coating methods was also included. Acid corrosion inhibitors are more well-documented than near-neutral corrosion inhibitors. Some of the inhibitors are suitable for industrial use. At the same time, a few sophisticated experimental procedures are required to comprehend the inhibitor's adsorption proclivity. UV-Visible, Fourier transform infrared spectroscopy, and XRD would provide useful information regarding inhibitor adsorption on metal surfaces that is currently lacking in the literature.

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