



# Anti-corrosive Properties of Synthetic Organic Compounds: A Review

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## Abstract

Corrosion poses a significant challenge in various industries, leading to substantial economic losses and safety concerns. The electrochemical reactions between metallic metals and their surroundings result in corrosion, which deteriorates the metals and frequently cause environmental contamination, financial losses, and safety issues. The paper summarizes the various organic inhibitors for steel and copper in hydrochloric acid and sulphuric acid and the methodology that we can use to find the properties of inhibition. There are numerous factors that influence the corrosion inhibition potential of these compounds, including the substituents and heteroatoms present in their molecular structures. An analysis of the inhibition of copper and steel corrosion using organic compounds is presented in the present review article. This review provides insights into the various organic inhibitors that inhibit corrosion through heterocyclic compounds. The focus of this review paper is on the novel contributions to corrosion inhibition, demonstrating how organic compounds can be used to protect steel and copper surfaces from corrosion.

**Keywords** Corrosion · Corrosion inhibitors · Concentration · Efficiency

## Abbreviations

|         |   |
|---------|---|
| EIS     | Electrochemical impedance spectroscopy          |
| PDP     | Potentiodynamic polarization                    |
| AFM     | Atomic force microscope                         |
| DFT     | Density functional theory                       |
| MD      | Molecular dynamic simulations                   |
| SEM     | Scanning electron microscope                    |
| EDS     | Energy dispersive spectroscopy                  |
| EDX     | Energy dispersive X-ray spectroscopy            |
| XPS     | X-ray photoelectron spectroscopy                |
| RDF     | Radial distribution function                    |
| MSD     | Mean square displacement                        |
| ICP-OES | Inductively coupled plasma-optical spectroscopy |

## 1 Introduction

### 1.1 General Introduction to Corrosion

Electrochemical reactions between metallic metals and their surroundings result in corrosion, which deteriorates the metals and frequently endangers the environment, financial interests, and process safety. Serious problems like altered mechanical characteristics, physical appearance, and material resistance are also brought up by corrosion [1]. This is an extensive and considerable issue that affects many industry sectors, including oil and gas, chemical along manufacturing industries. The situation of corrosion can cause serious economic losses also endangering human safety [2]. The most common corrosion complications are caused by breakdown in pipelines, leakage of chemicals, and sometimes fire in industrial areas; mostly when electrical and corroded components are present. Most factories in various sectors suffer from a variety of corrosion, including galvanic corrosion, uniform corrosion, crack corrosion, intergranular corrosion pitting, and erosion [3]. Corrosion causes enormous economic losses which have been approximated to 1–5% of the country's GDP, particularly in developed countries [4]. As a result, there is a constant demand for effective corrosion inhibitors to prevent or minimize corrosion damage.

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## 1.2 Introduction of Corrosion Inhibitors

Corrosion inhibitors: the synthetic substances that in tiny amounts help prevent metals from corroding in harsh settings. Because of excessive corrosive rates in the mentioned areas, refinery units, pipelines, steam generators, ballast tanks, and many more industrial divisions use corrosion inhibitors [5]. Acidic solution mediums are employed in many industries as pickling and cleaning agents to remove unwanted particles from the surfaces of containers which cause corrosion of the metal surface [6]. The most dominant method of protecting metals from corrosion is to incorporate a compound that can act as inhibitors in aggressive media [7]. Here a number of inhibitors we can use in aggressive media. Figure 1 shows four types of corrosion inhibitors; Environmental inhibitors, green inhibitors, organic inhibitors, and inorganic inhibitors; which minimize the corrosion on the metallic surfaces. Effective inhibitors are chosen according to their mode of action mechanism. Inhibitors should be effective even at high concentrations of acidic medium and high temperatures also. Furthermore, the inhibitory capacity of the substance is supported by the existence of a structure of adsorption active sites with lone pairs and orbitals, heterocyclic rings comprising nitrogen, phosphorus, oxygen, and sulfur atoms. These chemicals can either form a strong coordination connection with a metal atom or a surface passive film [8]. The effective inhibitors are then adsorbed on top of the metal while blocking the active sites [9]. Organic inhibitors work by being adsorbed on the metal and hindering the active sites by replacing molecules of water and creating a dense barrier coating to slow down the rate of corrosion [10].

All inhibitors shown in Fig. 1 are explained below and their advantages and disadvantages are discussed below:

### 1.2.1 Environmental Corrosion Inhibitors [11, 12]

Environmental corrosion inhibitors are substances that are added to environments to reduce the rate of corrosion of metals and other materials. The current trend for inhibitor usage

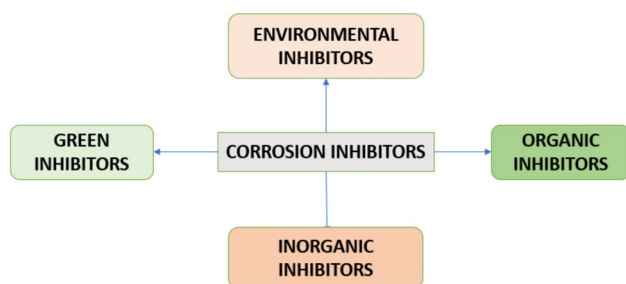


Fig. 1 Types of corrosion inhibitors

is towards more environmentally friendly green chemicals. For environmental protection, the scientific efforts have increased to study the inhibiting power of natural products like peels, seeds, fruit-shells and leaves that contain different organic compounds which (e.g. amino acids, alkaloids, flavonoids, pigments, tannins, etc.) suppress the dissolution reaction of metals and prevent the environmental pollution. In 1930, plant extracts (dried stems, leaves and seeds) of Celandine (*Chelidonium majus*) and other plants were used in  $H_2SO_4$  pickling baths. Animal proteins (by products of meat and milk industries) were also used for retarding acid corrosion. The additives used in acid, included flour, bran, yeast, a mixture of molasses and vegetable oil, starch and hydrocarbons (tars and oils).

Advantages and disadvantages of environmental corrosion inhibitors [13].

- *Advantages of environmental corrosion inhibitors*

1. These are environment-friendly and have less harmful effects.
2. These are easy to apply and is time saving.
3. These are renewable in nature.
4. The organic compounds present in the natural extracts improve the corrosion inhibition efficiency in metal surfaces.
5. These inhibitors breaks down themselves.

- *Disadvantages of environmental corrosion inhibitors*

1. These are less effective as compared to other inhibitors.
2. They can be more expensive to produce than traditional inhibitors, which can increase the overall cost for industries.

### 1.2.2 Green Corrosion Inhibitors

Green corrosion inhibitors are extracted from natural products or prepared from natural products (raw materials). Some organic corrosion inhibitors and polymer corrosion inhibitors fall under this category. Leaves, flowers, fruits, seeds, pericarp, or other parts of plants can be the sources of effective inhibition substances [12]. The extraction methods include soaking, heating reflux, enzymatic hydrolysis, Soxhlet extraction, and ultrasonic extraction methods. The efficiency of extraction of the active components depends on the solvent used, extraction temperature (60–80 °C for most plants), drying temperature (60–80 °C), extraction time, liquid–solid ratio, etc. Different green corrosion inhibitors

are isolated from different sources that help to minimize corrosion of various metals. A lot of research has been done on development of green corrosion inhibitors. The natural substances can serve as impressive corrosion inhibitors in the near future owing to their advantages which include easy accessibility, eco-friendliness, biodegradability on earth and non-toxicity [13].

Advantages and disadvantages of green corrosion inhibitors [14, 15].

- *Advantages of green corrosion inhibitors*

1. Green corrosion inhibitors are made up of natural resources like wood, seeds, leaves, etc.
2. These are less toxic and biodegradable in nature.
3. These are less costly and causes less pollution.
4. The extracts have good inhibition efficiency for metal corrosion in various media.

- *Disadvantages of green corrosion inhibitors*

1. These are less effective in some cases.
2. These are not compatible with all types of metals or materials.
3. These takes more time as compared to other types of corrosion inhibitors

### 1.2.3 Inorganic Corrosion Inhibitors

Inorganic corrosion inhibitors are substances that are added to a metal surface to prevent or slow down the corrosion process. They work by forming a protective layer on the surface of the metal, which prevents or limits contact with corrosive agents. Inorganic corrosion inhibitors can be classified based on their chemical composition, mode of action, and application. Metal salts such as chromates, molybdates, and phosphates are commonly used as corrosion inhibitors. These inhibitors are commonly used in the oil and gas industry. The inorganic phosphate inhibitor forms a protective layer on the surface, while the organic inhibitor provides additional protection by inhibiting corrosion [16].

Advantages and disadvantages of inorganic corrosion inhibitors.

- *Advantages of inorganic corrosion inhibitors*

1. These are effective at blocking anodic and cathodic sites.

2. These are effective in preventing corrosion especially in aggressive environments.
3. These are less expensive as compared to organic inhibitors and are cost effective options for large scale.
4. These are stable under a wide range of environmental conditions including high temperature.

- *Disadvantages of inorganic corrosion inhibitors*

1. These are toxic in nature.
2. The disposal and handling of these inhibitors requires stringent conditions.
3. They can cause scaling or precipitation in some cases.

### 1.2.4 Organic Corrosion Inhibitors

Synthetic organic corrosion inhibitors; are of two types as mentioned in Fig. 2 i.e. liquid-phase organic corrosion inhibitors and volatile organic corrosion inhibitors. Using organic chemicals, particularly heterocyclic compounds, provides the most effectual corrosion prevention techniques available today. Organic compounds with specific polar functional groups or coordination sites have effective corrosion inhibition properties [17]. It is one of the most popular and effective approaches because of its association with various advantageous qualities such as high inhibitory capacity, lesser cost, easier to apply, and recyclability [18]. During cleaning procedures in industries, heterocyclic compounds are introduced to aggressive solutions. Here heterocyclic compounds may adsorb on the surface of metal to reduce the risk of corrosion. Adsorption of heterocyclic compounds on metal creates a defensive bar that prevents aggressive electrolytes from corroding [19, 20]. The capacity of these inhibitors is because of the existence of many heteroatoms

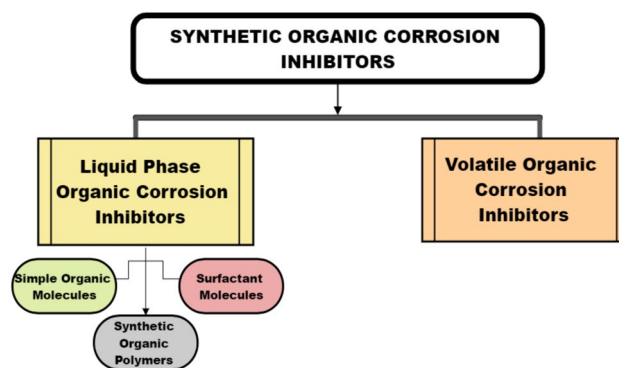


Fig. 2 Types of synthetic organic corrosion inhibitors

in the form of polar functional groups like,  $-\text{NH}_2$ ,  $-\text{NO}_2$ ,  $-\text{COOC}_2\text{H}_5$ , etc., as well as non-bonding or  $\Pi$ -electrons. During metal-inhibitor interactions, polar functional groups, non-bonding, and  $\Pi$ -electrons serve as adsorption center [21].

Advantages and disadvantages of organic corrosion inhibitors [22].

- *Advantages of organic corrosion inhibitors*

1. These seem to be highly effective and their cost is attractive.
2. These kinds of inhibitors are widely used and possess higher efficiency than all other inhibitors.
3. These inhibitors have highest corrosion inhibition efficiency.

- *Disadvantages of organic corrosion inhibitors*

1. These inhibitors need higher dosages to exert better effects.
2. The usage of these inhibitors was restricted due to high exploitation rates.
3. These are least eco-friendly.
4. The mechanism of these inhibitors to operate are often tedious.

**1.2.4.1 Liquid-Phase Organic Corrosion Inhibitors** The inhibitory efficiency of these organic compounds is related to the heterocyclic nature of the compounds with N, S, O and P heteroatoms in their molecules, which serve as reaction centers for adsorption on the metal surface. The inhibition efficiency of the heteroatoms in heterocyclic compounds follows the sequence  $\text{O} < \text{N} < \text{S} < \text{P}$ . The electron transfer from these inhibitors to the metal surface is facilitated by the availability of non-bonded (lone pairs) and  $\pi$ -electrons in the inhibitor molecules. Liquid-phase inhibitors are further classified into three types: simple organic molecules, synthetic organic polymers, and surfactant molecules [23, 24].

- *Simple organic molecules* Simple organic compounds such as azoles (imidazole, benzimidazole, benzotriazole, triazole, tetrazole), amines, urea, mercaptobenzothiazole (MBT), aldehydes, heterocyclic nitrogen compounds, sulfur-containing compounds, acetylenic compounds and also ascorbic acid, succinic acid, and tryptamine have been reported to be effective organic corrosion inhibitors.
- *Synthetic organic polymers* Organic polymeric materials can also be efficient corrosion inhibitors because they contain potent heteroatom functional groups that

form inhibitor (polymer)–metal ions complexes; which can occupy large zone over metallic surface and protect it from the corrosive media.

- *Surfactant molecules* Surfactants (Surface active agents) is another class of synthetic organic inhibitors, which have also been extensively used as commercial corrosion inhibitors and their inhibition efficiency may be attributed to their ability to affect the nature of metal surfaces and solution interfaces. It is generally assumed that adsorption of the surfactant molecules onto the metal surface is the first stage in the mechanism of surfactants as corrosion inhibitors in aggressive media. The adsorption process is influenced by the nature and the surface charge of the metal, the chemical structure of the surfactant, and the nature of the aggressive electrolyte.

**1.2.4.2 Volatile Organic Corrosion Inhibitors** Volatile Organic Corrosion Inhibitors (VOCIs) are compounds used to protect metal surfaces from corrosion. These inhibitors work by vaporizing and forming a protective layer on the metal surface, preventing the interaction of the metal with corrosive agents such as moisture and oxygen. These are used in packaging materials to protect metal parts during storage and transportation and applied in marine applications to protect ship parts and offshore structures. Due to their volatile nature, VOCIs can protect complex geometries and internal surfaces. Some VOCIs can be harmful to the environment due to their volatile nature and potential toxicity. VOCIs contain organic and inorganic chemical compounds able to vaporize and condense in the presence of moisture-forming thin films on metallic surfaces [25, 26].

**1.2.4.3 Shortcomings of Having Lack of Organic Corrosion Inhibitors [27–29]** Lack of organic corrosion inhibitors can lead to several significant shortcomings, particularly in industries where metal corrosion is a concern. Here are some of the main problems occurring due to lack of organic corrosion inhibitors:

- Without organic corrosion inhibitors, metal structures and components are more prone to rust and degradation, leading to more frequent maintenance and replacement needs.
- Corrosion can significantly reduce the lifespan of machinery, pipelines, and other metal structures, necessitating earlier-than-expected investments in replacements.
- Equipment failure due to corrosion can lead to unexpected downtime, disrupting production schedules and affecting overall operational efficiency.
- Corrosion can lead to leaks and spills, especially in the case of pipelines carrying hazardous materials. This

can result in environmental contamination and regulatory fines.

- Corroded surfaces can increase friction and resistance in mechanical systems, leading to reduced efficiency and higher energy consumption.
- In the absence of organic inhibitors, alternative corrosion control measures, such as cathodic protection or the use of more expensive corrosion-resistant materials, may be required, leading to higher overall costs.
- In industries like food and beverage, pharmaceuticals, and electronics, corrosion can contaminate products, affecting their quality and safety.
- Many industries are subject to strict regulations regarding corrosion control. Lack of adequate inhibitors can lead to non-compliance, legal issues, and potential shutdowns.

Corrosion inhibitors are frequently useful in industrial sectors to slow down the corrosion of metallic compounds in contact with an acidic medium. Chemical and electrochemical methodologies combined with analytical methods are applied to properly select effective inhibitors; still, there is a demand for a standardized procedure to describe the interplay between inhibitors and the surface of the metal in the hope of exploring new and much more efficient inhibitors. The inhibitor's activity is influenced by the structure of the molecule and electronic parameters; for instance; the highest occupied molecular orbital energy, the lowest unoccupied molecular orbital energy, and the HOMO–LUMO energy difference [30].

#### 1.2.4.4 Some Applications of Organic Corrosion Inhibitors in Various Sectors

**1. Organic corrosion inhibitors for Reinforced concrete**

Reinforcement corrosion is one of the major causes of degradation in concrete structures. A wide variety of types of corrosion-inhibiting admixtures for reinforced concrete are known. These include organic corrosion inhibitors such as formulations based on amines and alkanolamines (amino alcohols) [31]. When concrete is exposed to carbonation and/or to chloride salts, the embedded steel may cease to be passivated and start corroding at a significant rate. Since the volume of the corrosion product is normally several times greater than that of the original metal, the associated stresses in the concrete can lead to cracking and eventually to spalling [32]. Some authors also report that organic inhibitors help to decrease the chloride content in concrete and to promote a decrease on the chloride ion diffusion. Jamil HE et al. studied that the organic inhibitors studied in this work (preventive and curative amino alcohol-based inhibitors) reduced the corrosion rate of the reinforcing steel in solutions simulating concrete interstitial electrolyte contaminated with 2 g/l of NaCl and 4% (v/v) of inhibitor [33].

#### 2. Organic corrosion inhibitors used in oil and gas industry

In the petroleum industry, general and localized corrosion are the most common types of corrosion occurrences. The other large problem in operating pipe flow lines is internal corrosion, mainly due to stress corrosion cracking. The combination of corrosion and erosion is the main problem in pipe deterioration [34]. In the petroleum industry, one facet of the development of new oil and gas production is the stimulation process. Overall, the stimulation process involves many different aspects, including the acidizing portion utilized to stimulate the carbonate reservoir or for dissolving fines. Hydrochloric, hydrofluoric, acetic, or formic acids are injected into the well during the acidizing stimulation process which cause serious corrosion issues. In the absence of corrosion inhibitors (CIs), the general CR (corrosion rate) can be extremely high ( $> 100$  mm/y) and can increase exponentially with increasing temperatures and acid concentrations [35]. To control the corrosion damage of well tubulars, mixing tanks, coiled tubings, and other metallic surfaces, acids need to be inhibited by the use of an effective organic corrosion inhibitor solution. For stimulation applications, inhibitors are added to the acid fluids in batch-wise fashion; batch-wise refers to the single addition of the CI into the holding tank of the acid before the acid is used in the stimulation process [36]. Abiola et al. [37], reported that 3-(4-amino-2-methyl-5-pyrimidyl methyl)-4-methyl thiazolium chloride effectively prevents hydrogen evolution and corrosion of MS in 0.5 mol/L and 5 mol/L HCl at 30 °C.

#### 3. Organic corrosion inhibitors used in hydraulic metal structures

The hydraulic metal structures are exposed to harsh and complex stresses (corrosive stresses, physical loads, biological stresses, etc.). Corrosive stresses depend largely on the location of a metal structure. Hydraulic metal structures have significant exposure in several zones. The most effective and common method of corrosion protection is to paint organic coatings on the surface of metal structures. The organic coatings on hydraulic metal structures can be exposed to various environmental factors, such as the temperature, humidity, ultraviolet radiation (UV), chloride ion and mechanical stress. The organic coatings deteriorate with the increase of exposure time, and periodic recoating is necessary for hydraulic metal structures to prevent environmental attack and to extend their service life [38].

#### 4. Organic corrosion inhibitors used in electronics industry

Numerous field failure returns of electronics are marked as “no failure found”, yet many of these failures are likely due to corrosion. Electronic equipment components, computers, integrated circuits (IC) and microchips in indoor atmospheres are exposed to a variety of environmental conditions and frequently corrosion failure of these devices

occurs. Corrosion is becoming an even more significant factor in the reliability of electrical and electronic equipment. Within the last decade, the electronic and electrical industries are increasingly applying more Vapour Phase Corrosion Inhibitors (VCI) for electronic components and devices. As electronics continue to shrink in size and grow in capacity, the importance of corrosion control increases. The corrosion of small and micro components of silver causes extensive losses to the electronics industry due to reject product, problems with soldering processes and production delays. The silver surface becomes tarnished by the effect of  $H_2S$  and, depending on exterior pollution, the problem can occur at controlled indoor conditions in clean rooms too [39, 40].

### 1.3 Corrosion on Mild Steel

Mild steel (M-steel) is one of the most often used pipeline materials in the gas and oil industries. It is widely utilized as a building material for domestic and industrial purposes due to its abundance, low cost, and strong mechanical power. They do, however, dissolve rapidly in acid during the cleaning, pickling, and descaling procedures. However, corrosion of steel pipes is a significant issue that has resulted in several failures. Because of its corrosive nature, it should not be exposed to acids. Inhibitors can adsorb on the exterior of mild steel and hinder active sites, reducing the rate of corrosion. Mild steel degradation has been long a worry due to its extremely high corrosion rate in hostile solutions and atmospheres. As a result, the application of coatings is highly advised to preserve these alloys at moderate temperatures, even if it may cause minor flaws (tiny cracks and holes) on the substrate's surface. Mineral solutions are comprehensively used in a diversity of sectors, including descaling, pickling along with many more. It is consequently critical to add inhibitors to mineral acid solutions used in various operations to reduce the rate of corrosion attack and the amount of acid consumed [41–44].

### 1.4 Corrosion on Copper

Copper, which has a reddish-orange color, is 5th most prevalent metal in the geosphere and also immensely useful in both pure and alloying forms. It is an essential non-ferrous things utilized in industry due to its qualities like high conductivity, mechanical adaptability, also feasibility [45]. Copper and its alloys have been employed in a wide range of manufacturing units, including aerospace, automobile manufacturing, and bridge construction. These are highly prized because they are widely used in the manufacture of cable pipelines in the electronic and power industries, as well as heat exchangers and cooling towers. They are, however, susceptible to corrosion from the surrounding media, which can cause considerable economic and energy losses,

as well as serious accidents. Copper can be protected against corrosion through coatings, altering the solution environment, and other ways [46–48]. Copper is considered a noble metal because it produces a protective film that provides enough reluctance to corrosion in the atmosphere and under certain chemical circumstances [49]. However, depending on the environmental circumstances, corrosion on the copper surface may occur because of the existence of oxygen with some aggressive anions such as chloride and sulfate ions [50].

## 1.5 Literature Survey

It has been found from the literature that numerous synthetic compounds are reported that act as inhibitors of corrosion as shown in Tables 1 and 2.

The Table 1 provides an overview of the efficiency of various organic corrosion inhibitors, highlighting how their effectiveness changes with different concentrations in different acidic mediums for protecting the metals (mild steel) from being corroded. The concentration is the amount of inhibitor used. The effectiveness of the inhibitor in reducing corrosion, expressed as a percentage (efficiency of the inhibitor). Efficiency indicates the reduction in corrosion rate when the inhibitor is used compared to a control sample without the inhibitor. Higher percentages indicate greater efficiency. The type of acidic environment in which the inhibitor's efficiency is tested (e.g., hydrochloric acid (HCl), sulfuric acid ( $H_2SO_4$ )). The table highlights how the efficiency of organic inhibitors varies depending on the type of metal, concentration of the inhibitor, and the specific acidic environment. This data is important for selecting the most effective inhibitor and concentration for specific applications, ensuring optimal protection of metals in acidic conditions [51].

The Table 2 Summarizes the use of different organic corrosion inhibitors used for the protection of copper from being corroded. As clear from the Table 2, different methods had been used to find the efficiency. The data helps in selecting the most effective inhibitor for specific applications to prolong the lifespan of metals (copper) and reduce maintenance costs.

## 1.6 Methodologies Used for the Detection of Corrosion Inhibitors

### 1.6.1 Weight Loss Technique

Weight loss is a typical way of determining the efficiency of inhibitors. This approach involves weighing a metal sample before and after it has been exposed to a corrosive environment, with or without an inhibitor. The steps

**Table 1** List of some of the synthetic organic compounds for mild steel in the presence of hydrochloric acid and sulfuric acid

| Sr. no. | Name of inhibitor   | Efficiency of inhibitor                      | Concentration of inhibitor | Adsorption isotherm                      | Techniques  | Acid used                             | References |
|---------|---|--|----------------------------|--|---|---------------------------------------|------------|
| 1.      | Tetraglycidyl ether of tetra bis-phenol A of urea   | 93%  | 2002.29 ppm                | Langmuir                                 | Weight loss, EIS, PDP, AFM, DFT, MD simulations, FTIR                                   | 1 M HCl                               | [74]       |
| 2.      | TGEAP (trifunctional epoxy resin)   | 90%  | 10 <sup>-3</sup> M         | Langmuir                                 | PDP, EIS  | 1 M HCl                               | [75]       |
| 3.      | Pentalicydil ether pentabis phenol A of phosphorus (PBA)  | 96.25%                                       | 10 <sup>-3</sup> M         | Langmuir                                 | Gravimetric measurements, SEM/EDS, EIS, PDP   | 0.5 M H <sub>2</sub> SO <sub>4</sub>  | [76]       |
| 4.      | amino tetrazole (ATA)   | 87.83%                                       | 1000 ppm                   | Langmuir and Frumkin adsorption isotherm | DFT, MD simulations   | 0.05 M H <sub>2</sub> SO <sub>4</sub> | [77]       |
| 5.      | 3-Nitrophthalic acid  | 80.51%                                       | 400 ppm                    | Langmuir                                 | FTIR, UV-visible spectroscopy, EIS, SEM, AFM, CA  | 1 M HCl                               | [78]       |
| 6.      | [E]4-(4-(dimethylamino)benzylidene amino)-5-(pyridine-4-yl)-2H-1,2,4-triazole-3(4H)-thione                  | 90%  | 250 ppm                    | Langmuir                                 | SEM, EDX spectroscopy, XPS  | 1 M H <sub>2</sub> SO <sub>4</sub>    | [79]       |
| 7.      | (2E)-3-(6-phenylimidazo[2,1-b][1,3]-thiazol-5-yl)-1-(2,4,6-trimethylphenyl)prop-2-en-1-one                  | 97%  | 10 <sup>-4</sup> M         | Langmuir                                 | SEM, MD simulations   | 1 M HCl                               | [80]       |
| 8.      | Acetonaph[1,2-b]quinoxalin  | 80%  | 10 <sup>-5</sup> M         | Langmuir                                 | Density functional theory   | 0.5 M H <sub>2</sub> SO <sub>4</sub>  | [81]       |
| 9.      | Indeno-1-one[2,3-b]quinoxalin   | 81%  | 10 <sup>-5</sup> M         | Tenkin's                                 | Density functional theory,  | 0.5 M H <sub>2</sub> SO <sub>4</sub>  | [82]       |
| 10.     | Polyvinyl alcohol-sulphamic acid  | 84%  | 6000 ppm                   | Langmuir                                 | Weight loss, potentiodynamic polarization, electrochemical impedance spectroscopy, FTIR | 1 M HCl                               | [52]       |
| 11.     | N-[4-(1,3-benzodithiazol-2-yl carbonyl)phenyl]quinoline-6-carboxamide                                       | 90%  |                            | Langmuir                                 | Weight loss, EIS, PDP   | 1 N HCl                               | [83]       |
| 12.     | (4-(3-mercapto-5,6,7,8-tetrahydro-[1,2,4]triazole[4,3-b][1,2,4,5]tetrazin-6-yl)phenol)                      | 67%  | 0.5 mM                     | Langmuir                                 | EIS, electrochemical frequency modulation   | 1 M HCl                               | [41]       |
| 13.     | (3,5-dimethyl-1H-pyrazol-1-yl)-(4-((3,4-dimethoxybenzylidene)amino)phenyl)methanone                         | 95.5%  | 400 ppm                    | Langmuir                                 | Weight loss, FTIR, NMR  | 1 M HCl                               | [53]       |
| 14.     | Bis-phenyl urea-aliphatic amine   | 95.1%  | 50mgL <sup>-1</sup>        | Langmuir                                 | NMR, DFT  | 1 M HCl                               | [84]       |
| 15.     | 2-(2-hydroxyphenyl) benzothiazole   | 95%  | 0.07 mM                    | Langmuir                                 | Weight loss, EIS, PDP, and morphology characterization                                  | 1 M HCl                               | [85]       |
| 16.     | 5((6-methyl-2-oxo-2H-chromon-4-yl)thiomethyl)-2((N-(3-methyl-quinoxaline-2(1H)one) methyl)-1,3,4-oxadiazole | 84.85%                                       | 50 ppm                     | Langmuir                                 | EIS, PDP, weight loss, SEM, DFT   | 0.5 M HCl                             | [86]       |
| 17.     | 2-N-phenylamino-5-(3-phenyl)-3-oxo-1-propyl)-1,3,4-oxadiazole   | 71.54% (for 100 ppm)<br>92.19% (for 500 ppm) | 100 ppm<br>500 ppm         | Langmuir                                 | SEM, DFT  | 1 M HCl                               | [87]       |

Table 1 (continued)

| Sr. no. | Name of inhibitor   | Efficiency of inhibitor | Concentration of inhibitor | Adsorption isotherm              | Techniques  | Acid used                          | References |
|---------|---|-------------------------|----------------------------|----------------------------------|---|------------------------------------|------------|
| 18.     | Glucose derivative based on 8-hydroxyquinoline  | 96.5%                   | $10^{-3}$ M                | Langmuir                         | Weight loss, PDP, EIS   | 1 M HCl                            | [56]       |
| 19.     | S-benzyl-O, O'-bis (2-naphthyl) dithiophosphate   | 97.44%                  | 100 ppm                    | Physiosorption and chemisorption | Weight loss, PDP, EIS, SEM, quantum chemical calculation  | 1 M HCl                            | [88]       |
| 20.     | Bis(1H-benzo[d]imidazole-2-yl) thio) methane  | 97.1%                   | $10^{-3}$ M                | Langmuir                         | Weight loss, PDP, SEM, EDX, DFT, and MD simulation  | 1 M HCl                            | [89]       |
| 21.     | [4-(4-chloro-phenyl azo)-3-hydroxy-5-phenylamino-thio-phen-2-yl]-phenyl-methane   | 95%                     | $5 \times 10^{-5}$ M       | Langmuir and Henry               | MD simulations, surface analysis, AFM, SEM, and MC simulations  | 1 M HCl                            | [90]       |
| 22.     | Triphenyltin-2-thiophene carboxylate  | 97%                     | $10^{-3}$ M                | Langmuir                         | Weight loss, EIS, PDP   | 1 M HCl                            | [91]       |
| 23.     | 4-methyl-1,2-dihydro-3H-benzo[b][1,4] diazepin-3-one  | 90.22%                  | $10^{-3}$ M                | Langmuir                         | EIS, PDP, weight loss, SEM, DFT, MC simulations   | 1 M HCl                            | [92]       |
| 24.     | 4-phenyl-decahydro-1H-1,5-benzodiazepin-2-one   | 90.98%                  | 0.001 M                    | Langmuir                         | EIS, PDP, SEM, DFT, and MD simulations  | 1 M HCl                            | [93]       |
| 25.     | N-(2-aminophenyl)-2-(5-methyl-1H-pyrazole-3-yl) acetamide   | 93%                     | 5 mM                       | Langmuir                         | Density functional theory, MC simulations, scanning electron microscope, energy dispersive X-ray spectroscopy | 1 M HCl                            | [94]       |
| 26.     | Carboxymethyl cellulose   | 94.24%                  | 1000 ppm                   | Langmuir                         | Weight loss, electrochemical measurements, EIS, SEM   | 1 M HCl                            | [95]       |
| 27.     | Hexaglycidyl-N-phenylamine-propoxy-N,N,N-triphenyl propane-1,3-diamine (ERH) and octaglycidyl N,N,N,N-tetraphenylamine-N,N,N,N-tetrapropoxy methylene diamine (ERO)   | 95.6% and 95.4%         | 257 ppm                    | Langmuir                         | Polarization curve, EIS, SEM, global quantum chemical descriptors, MD simulations, DFT, Hartree fork method   | 1 M HCl                            | [96]       |
| 28.     | Ethyl 1-amino-3-(2-chlorophenyl)-5,10-dioxo-5,10-dihydro-1H-pyrazolo[1,2-b] phthalazine-2-carboxylate (Py-1) and ethyl 1-amino-5,10-dioxo-3-(p-tolyl)-5,10-dihydro-1H-pyrazolo-[1,2-b] phthalazine-2-carboxylate (Py-2) | 96.7% and 90.9%         | $10^{-6}$ to $10^{-3}$ M   | Langmuir                         | EIS and PDP, SEM/EDX, MD simulations, DFT   | 2 M H <sub>2</sub> SO <sub>4</sub> | [97]       |



Table 1 (continued)

| Sr. no. | Name of inhibitor   | Efficiency of inhibitor      | Concentration of inhibitor | Adsorption isotherm | Techniques   | Acid used | References |
|---------|---|------------------------------|----------------------------|---------------------|--|-----------|------------|
| 29.     | (E)-4,4(E)-4,4'-((4-(2-amino-6-phenyl-2H-1,3-thiazin-4-yl)phenyl) diazenyl) methylene) bis(6-phenyl-6H-1,3-thiazin-2-amine) ( <b>ATPA</b> ) and (E)-1-(4((bis (5-amino 1,3,4-thiadiazol-2-yl) methyl) diazenyl) phenyl) ethenone. ( <b>ATPE</b> )   | 97.11% and 96.02%            | 200 ppm                    | Langmuir            | EIS, PDP, field emission SEM, EDX, AFM, XPS, DFT, monte-carlo simulations, MD simulations                        | 15% HCl   | [98]       |
| 30.     | ( <b>MA-1341</b> )-5'-(naphthalene-2-yl)-[2,2'-bithiophene]-5-carboxamide hydrochloride salt<br>( <b>MA-1348</b> )-5'-(isoquinoline-4-yl)-[2,2'-bithiophene]-5-carboxamide hydrochloride salt<br>( <b>MA-1340</b> )-5'-(4-chlorophenyl)-2,2'-bithiophene-5-carboxamide hydrochloride salt | 93.55% and 95.14% and 91.05% | 30 × 10 <sup>-6</sup> M    | Langmuir            | PDP, EIS, EDX, DFT, SEM, FTIR, XPS, weight loss  | 1 M HCl   | [99]       |
| 31.     | ( <b>FRI78</b> )- (E)-3-(5-bromo-2-hydroxystyryl)quinoxaline-2(1H)-one<br>( <b>FRI79</b> )- (E)-3-(5-fluoro-2-hydroxystyryl)quinoxaline-2-(1H)-one  | 90.9% and 91.5%              | 10 <sup>-3</sup> M         |                     | PDP, EIS, XRD, SEM/EDS, MD simulations, DFT  | 1 M HCl   | [100]      |
| 32.     | ( <b>HHQ</b> )-2-(2,3-dimethoxyphenyl)-1,4-dihydroxyquinoline and<br>( <b>NHQ</b> )-2-(2,3-dimethoxyphenyl)-6-nitro-1,4-dihydroquinoxaline  | 95.3% and 91.5%              | 10 <sup>-3</sup> M         | Langmuir            | DFT, MC simulations, MD simulations, EIS, SEM  | 1 M HCl   | [101]      |
| 33.     | ( <b>HQ</b> )- 2-(2,4-dichlorophenyl)-1,4-dihydroquinoxaline and<br>( <b>CQ</b> )- 2-(2,4-dichlorophenyl)-6-methyl-1,4-dihydroquinoxaline   | 91% and 94.2%                | 10 <sup>-3</sup> M         | Langmuir            | Stationary and transient techniques, SEM, EDS, DFT, Quantum chemical descriptors (QCD), MD simulations, RDF, MSD | 1 M HCl   | [102]      |

Table 1 (continued)

| Sr. no. | Name of inhibitor  | Efficiency of inhibitor      | Concentration of inhibitor | Adsorption isotherm | Techniques  | Acid used | References |
|---------|--|------------------------------|----------------------------|---------------------|---|-----------|------------|
| 34.     | <b>(Q-CH<sub>3</sub>)</b> - 6-methyl-2,3-diphenylquinoxaline<br><b>(Q-NO<sub>2</sub>)</b> - 6-nitro-2,3-diphenylquinoxaline<br><b>(Q-H)</b> - 2,3-diphenylquinoxaline  | 90.2% and 87.6% and 92.4%    | 10 <sup>-3</sup> M         | Langmuir            | SEM-EDS, DFT, and MD simulations                    | 1 M HCl   | [103]      |
| 35.     | <b>(NSQN)</b> - (E)- 3-(4-dimethylamine)quinoxaline-2(1H)-one and<br><b>(CSQN)</b> - (E)-3-(4-chlorostyryl)quinoxaline-2(1H)-one   | 96% and 92%                  | 10 <sup>-3</sup> M         | Langmuir            | SEM, DFT, MD simulations, EIS, PDP                  | 1 M HCl   | [104]      |
| 36.     | <b>a)</b> 2-(prop-2-yn-1-yl)-4-(p-tolyl)phthalazin-1(2H)-one and<br><b>b)</b> 4-(4-chlorophenyl)-2-(prop-2-yn-1-yl)phthalazine-1(2H)-one   | 93.4% to 88.5%               | 21 × 10 <sup>-6</sup> M    | Langmuir            | Weight loss, SEM, FTIR, AFM, DFT                    | 1 M HCl   | [105]      |
| 37.     | <b>(TAPD-I)</b> - 2-((1H-indol-2-yl)thio)-6-amino-4-(4-nitrophenyl)pyridine-3,5-dicarbonitrile<br><b>(TAPD-II)</b> - 2-((1H-indol-2-yl)thio)-6-amino-4-phenylpyridine-3,5-dicarbonitrile<br><b>(TAPD-III)</b> - 2-((1H-indol-2-yl)thio)-6-amino-4-(4-hydroxyphenyl)pyridine-3,5-dicarbonitrile | 91.30% and 93.04% and 96.95% | 16.3 × 10 <sup>-5</sup> M  | Langmuir            | Weight loss, SEM, EDX, DFT, MD simulations          | 1 M HCl   | [106]      |
| 38.     | <b>POX</b> - 2-phenyl 5-(pyridine-3-yl)-1,3,4-oxadiazole and<br><b>4-PMOX</b> - 2-(4-methoxyphenyl)-5-(pyridine-3-yl)-1,3,4-oxadiazole   | 97.83% and 98%               | 500 ppm                    | Langmuir            | EIS, PDP, SEM, EDX, UV-visible, RDF, MSD            | 1N HCl    | [107]      |
| 39.     | <b>PMOT</b> - 5-(phenoxymethyl)-1,3,4-oxadiazole-2(3H)-thione and<br><b>BOT</b> - 5-benzyl-1,3,4-oxadiazole-2(3H)-thione   | 88.93% and 85.99%            | 300 ppm                    | Langmuir            | Weight loss, EIS, PDP, SEM-EDX, DFT, MD simulations | 1 M HCl   | [108]      |

Table 1 (continued)

| Sr. no. | Name of inhibitor   | Efficiency of inhibitor                  | Concentration of inhibitor | Adsorption isotherm | Techniques   | Acid used                            | References |
|---------|---|--|----------------------------|---------------------|--|--------------------------------------|------------|
| 40.     | <b>IM<sub>1</sub></b> - 4-(4,5-bis-(4-methoxyphenyl)-1H-imidazol-2-yl)phenol<br>and<br><b>IM<sub>2</sub></b> - 4-(4,5-bis(4-methoxyphenyl)-1H-imidazol-2-yl) benzenamine<br>and<br><b>IM<sub>3</sub></b> - 2,4,5-tris(4-methoxyphenyl)-1H-imidazole | 96%<br>and<br>94%<br>and<br>92%          | 1 mM                       | Langmuir            | Microwave irradiation method, SEM, XPS, XRD, DFT   | 0.5 HCl                              | [109]      |
| 41.     | <b>Qe<sub>2</sub>-Br</b> : 5-(2-bromoethoxy)methyl) quinolin-8-ol<br><b>Qc<sub>3</sub>-Br</b> : 5-(3-bromopropoxymethyl) quinolin-8-ol  | 96%<br>and<br>96%                        | 1 mM                       | Langmuir            | FTIR, NMR, elementary analysis, weight loss, PDP and EIS, DFT, MC and MD simulations, ICP-OES, UV-visible spectroscopy, SEM, EDS | 1 M HCl                              | [110]      |
| 42.     | <b>5-FIA</b> : 5-fluoro-1H-indazole<br><b>5-CIA</b> : 5-chloro-1H-indazole  | 90.4%<br>and<br>94.3%                    | 1 mM                       | Langmuir            | SEM, AFM, XPS, MD simulations  | 0.5 M H <sub>2</sub> SO <sub>4</sub> | [111]      |
| 43.     | <b>FPT</b> : 2-amino-4-(4-fluorophenyl)-thiazole<br><b>CPT</b> : 2-amino-4-(4-chlorophenyl)-thiazole<br><b>BPT</b> : 2-amino-(4-bromophenyl)-thiazole   | 79.52%<br>and<br>93.49%<br>and<br>96.71% | 1 mM                       | Langmuir            | Electrochemical measurements, MD simulations, quantum calculations   | 0.5 H <sub>2</sub> SO <sub>4</sub>   | [112]      |
| 44.     | <b>2A5MT</b> : 2-amino-5-mercapto-1,3,4-thiadiazole<br><b>2MT</b> : 2-mercaptothiazoline  | 99.8%<br>and<br>98.9%                    | 10 mM                      | Langmuir            | linear polarization resistance and EIS, PDP  | 1 M H <sub>2</sub> SO <sub>4</sub>   | [113]      |
| 45.     | <b>2B54NPO</b> : 2-benzyl-5-(4-nitrophenyl)-1,3,4-oxadiazole<br>and<br><b>24MO5POO</b> :<br>2-(4-methoxyphenyl)-5-(phenoxymethyl)-1,3,4-oxadiazole  | 96.54%<br>and<br>92.19%                  | 300 ppm                    | Langmuir            | EIS, weight loss, SEM, PDP, quantum chemical calculations, EDX   | 1 M HCl                              | [114]      |
| 46.     | Pyrazole-acetamide schiff bases   | 94.9%                                    | 10 <sup>-4</sup> M         | Langmuir            | Electrochemical studies, scanning electron microscopy, energy-dispersive X-ray   | 1 M HCl                              | [115]      |
| 47.     | Subphthalocyanine chloride  | 97.6%                                    | 150 ppm                    | -                   | Weight loss, Polarization studies, electrochemical impedance spectroscopy  | 1 M HCl                              | [116]      |

**Table 2** List of some of the synthetic organic compounds for copper in the presence of hydrochloric acid and sulfuric acid

| Sr. no. | Name of inhibitor   | Efficiency of inhibitor | Concentration of inhibitor | Adsorption isotherm used | Techniques used   | Acid used                            | References |
|---------|---|-------------------------|----------------------------|--------------------------|---|--------------------------------------|------------|
| 1.      | DNA   | 92%                     | 40 ppm                     | Langmuir                 | Electrochemical measurements, microwave surface observation, XPS, molecular dynamic simulations | 0.5 M H <sub>2</sub> SO <sub>4</sub> | [77]       |
| 2.      | <b>MeAT:</b> 3,5-bis(4-methylphenyl)-4-amino-1,2,4-triazole<br><b>MxAT:</b> 3,5-bis(4-methoxyphenyl)-4-amino-1,2,4-triazole                           | 84.6% and 87.9%         | 257 ppm                    | Langmuir                 | Electrochemical impedance spectroscopy, scanning electron microscope                            | 1 M HCl                              | [117]      |
| 3.      | (E)-1-(4-methoxyphenyl)-3-(6-phenylimidazol[2,1-b]thiazol-5-yl)-prop-2-en-1-one   | 96.9%                   | 10 <sup>-4</sup> M         | Langmuir                 | EIS, PDP, SEM, DFT, and MD simulations  | 1 M HCl                              | [118]      |
| 4.      | <b>ATP:</b> 4-(2-aminothiazole-4-yl)-phenol<br><b>PTA:</b> 4-phenylthiazole-2-amine<br><b>TATD:</b> 4,4'-(thiobis(2-aminothiazole-5,4-diyl)) diphenol | 90%<br>For all          | 0.1 to 2 mM                | Langmuir                 | PDP, EIS, AFM, SEM, DFT, and MD simulations   | 1 M HCl                              | [119]      |
| 5.      | 2-(4-morpholiniothio) benzothiazole   | 94%                     | 1 mM                       | Langmuir                 | EIS, PDP, Weight loss, SEM  | 0.5 H <sub>2</sub> SO <sub>4</sub>   | [120]      |
| 6.      | 2-amino-6-(methylsulphonyl) benzothiazole   | 95.95%                  | 3 mM                       | Langmuir                 | XPS, FTIR, SEM, AFM, weight loss  | 0.5 M H <sub>2</sub> SO <sub>4</sub> | [121]      |
| 7.      | <b>LMS:</b> levamisole<br><b>PIZ:</b> 4-phenylimidazole   | 99.03% and 95.84%       | 8 mM                       | Langmuir                 | XPS, SEM, AFM   | 0.5 M H <sub>2</sub> SO <sub>4</sub> | [122]      |
| 8.      | 2-amino-5-ethylthio-1,3,4-thiadiazole   | 78%                     | 10 mM                      | Langmuir                 | Weight loss, PDP, EIS, SEM, EDX   | 0.5 M HCl                            | [123]      |
| 9.      | 2-amino-6-(methylsulfonyl) benzothiazole  | 95.95%                  | 3 mM                       | Langmuir                 | Weight loss, FTIR, XPS, SEM, AFM  | 0.5 M H <sub>2</sub> SO <sub>4</sub> | [121]      |
| 10.     | 2-(2-chlorophenyl)-1H-benzimidazole   | 92.3%                   | 5 M                        | Langmuir                 | SEM, laser scanning confocal microscope (LSCM)  | 0.5 M H <sub>2</sub> SO <sub>4</sub> | [124]      |
| 11.     | 1-b]thiazol-5-yl)prop-2-en-1-one (MF-PIT), (E)-1-(5-methylfuran-2-yl)-3-(6-phenylimidazol[2,  | 97.5%                   | 10 <sup>-4</sup> M         | Langmuir                 | DFT, PDP, MF-PIT  | 1 M HCl                              | [125]      |
| 12.     | Tolyltriazole   | 96.1%                   | 20 ppm                     | Langmuir                 | Electrochemical studies,  | 0.1 M                                | [126]      |

involved in weight loss methods are represented in Fig. 3. The weight loss data was estimated using the equations below [52].

$$\eta\% = \frac{W_o - W_i}{W_o} \times 100$$

Srimathi et al. [52], achieved maximum corrosion inhibition efficiency of polyvinyl alcohol; which was 90.54% at 6000 ppm by using the weight loss method. Jasim et al. [53], achieved maximum corrosion inhibition efficiency of (3,5-dimethyl-1H-pyrazol-1-yl) (4-((3,4-dimethoxybenzylidene) amino) phenyl) methanone; 95.9% at 400 ppm at 60 °C by weight loss method.

## 1.6.2 Electrochemical Impedance Spectroscopy (EIS)

It's a potent approach used in research to examine the electrochemical behavior of a system, particularly the interactivity between the metal surface, its surroundings, and the inhibitor. EIS technique comes up with information on reductive and capacitive behavior at the contact, allowing to evaluation the compound's performance as an inhibitor [54, 55]. The principle of electrochemical impedance spectroscopy involves applying small amplitude, alternating current (AC) signals across an electrochemical cell over a range of frequencies.

Rbaa et al. [56], achieved maximum corrosion inhibition efficiency of 8-hydroxyquinoline; 96.5% at 10<sup>-3</sup> M by the EIS method.

**Fig. 3** Steps involved in Weight Loss technique

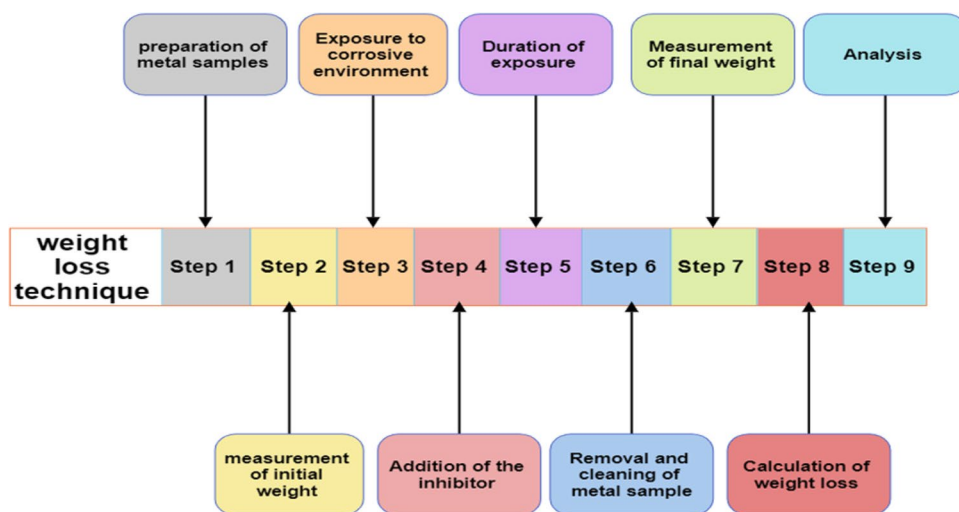


Figure 4 shows the working of the EIS technique using a working electrode, counter electrode, and reference electrode. The sample to be studied for its corrosion inhibition properties is placed in the beaker containing all the electrodes which are further connected to the EIS frequency response analyzer. The analyzer is connected to the computer system or recorder which records the data or graphs for the technique.

**1.6.3 Potentiodynamic Polarization**

PDP is one of the most generally acknowledged methods for determining a specimen’s corrosion. The potential difference is determined between reference and working electrodes. Ddifference is applied between two electrodes, and the resulting current is determined. It is a widely used electrochemical technique for analyzing metal behavior in a specific environment and determining corrosion susceptibility. The principle of potentiodynamic polarization involves sweeping the potential of an electrode (metal sample) linearly or logarithmically over a certain voltage range while measuring the resulting current.

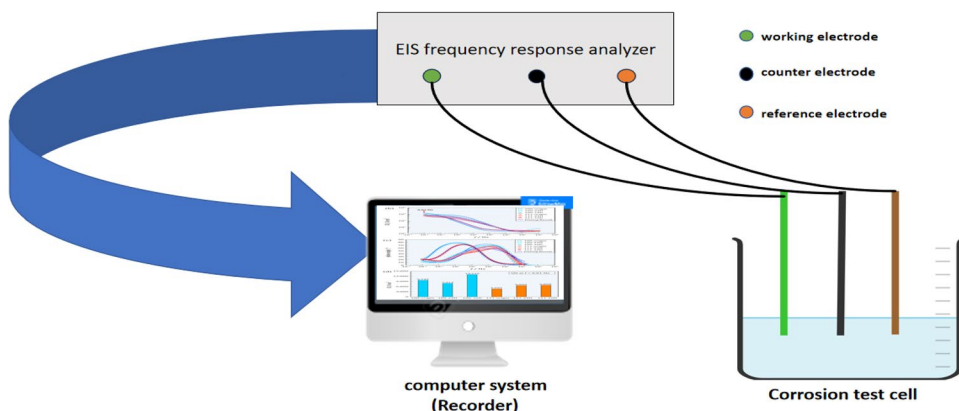
Rbaa et al. [56], show that the maximum corrosion inhibition efficiency of 8-hydroxyquinoline is 93.8% at  $10^{-3}$  M by the PDP method.

Potential versus resulting current curve:  
It involves two regions:

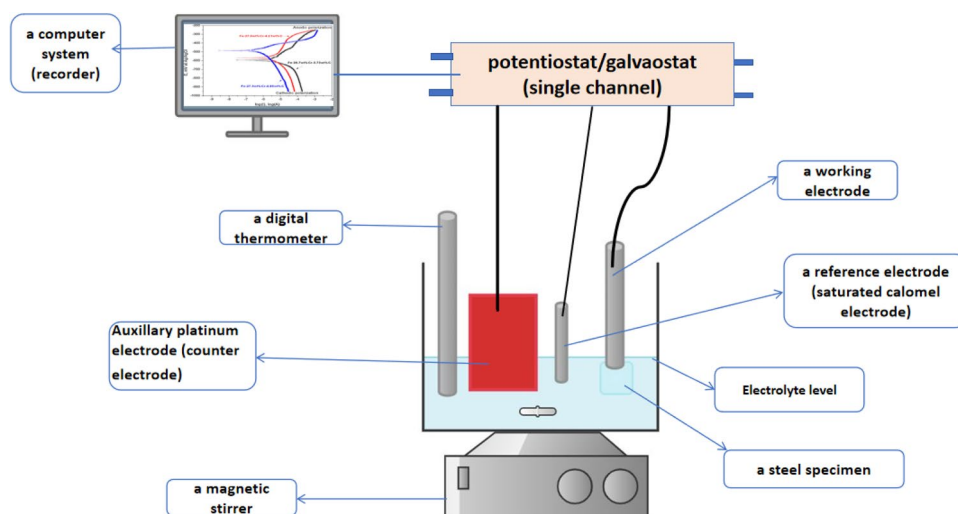
- Cathodic region (where reduction reaction occurs)
- Anodic region (where oxidation reaction occurs)

Figure 5 shows the basic principle and working of the PDP method. In this method, a beaker contains a magnetic bead, a digital thermometer, a reference electrode (standard calomel electrode), an auxiliary platinum electrode as well as a working electrode attached to a steel specimen; is placed over a magnetic stirrer. The working electrode, reference electrode, and auxiliary platinum electrode; are connected to potentiostatic/galvanostatic, which is further connected to a computer system that records the data.

**Fig. 4** Schematic diagram of Electrochemical Impedance Spectroscopy method



**Fig. 5** Schematic diagram showing the working of the Potentiodynamic Polarization method



#### 1.6.4 Atomic Force Microscopy

AFM is a kind of scanning probe microscopy developed in 1985 to measure local attributes (e.g., surface topography) with a probe. AFM is one method for understanding metal corrosion properties. This approach is applied to study the properties of surface layers in various materials, including ceramics, metals, polymers, and organic/inorganic composites [57]. Several imaging modalities are now available, which provide information about the sample surfaces as well as full three-dimensional topographies. Some of these include contact mode, tapping (or intermittent touch), and non-contact mode [58]. This technique's surface morphology can be used to investigate corrosion phenomena and the inhibitory impact of corrosion inhibitors [59]. Surface roughness can be used to characterize the inhibitory capacity of corrosion inhibitors. The rougher surface is related to the deterioration of the metal surface, resulting in an increased corrosion rate [60].

#### 1.6.5 SEM (Scanning Electron Microscope)

SEM is an electron microscope that results in high-resolution images of surfaces of bulk and nanomaterials at nanoscale levels. The images produced by SEM have two-dimensional and three-dimensional appearances, which are important for assessing the surface features of the specimens [61]. It is being employed in a variety of polymers as well as applications, surface roughness, including fiber-matrix adhesion and phase boundaries in blends [62].

#### 1.6.6 UV Spectroscopy

UV spectroscopy is utilized to determine the absorbance of a substance in solution. It has been used extensively in a diversity of settings to aid in qualitative as well as quantitative

analysis and reaction monitoring. UV absorption spectroscopy can help organic chemists monitor reactions and detect compounds online or offline. It can also be used for simple purposes like displaying pH [63]. UV spectroscopy is utilized to better understand corrosion and inhibitory mechanisms. It is used to identify the reactions taking place throughout the corrosion and inhibition processes [64].

Figure 6 shows the basic principle and working of the UV-Vis spectrophotometer. It includes mirrors, UV and visible light sources, slits, diffraction grating, filter, reference and sample cuvettes, lenses, detectors, reference and sample beams, and recorder.

A solution of sample is placed in the sample cuvette and the reference cuvette is filled with reference solvent used to dissolve the sample. A command is given to the system for recording the absorbance and graph for the sample. The absorbance and graph data are displayed over the recorder.

#### 1.6.7 FTIR Spectroscopy

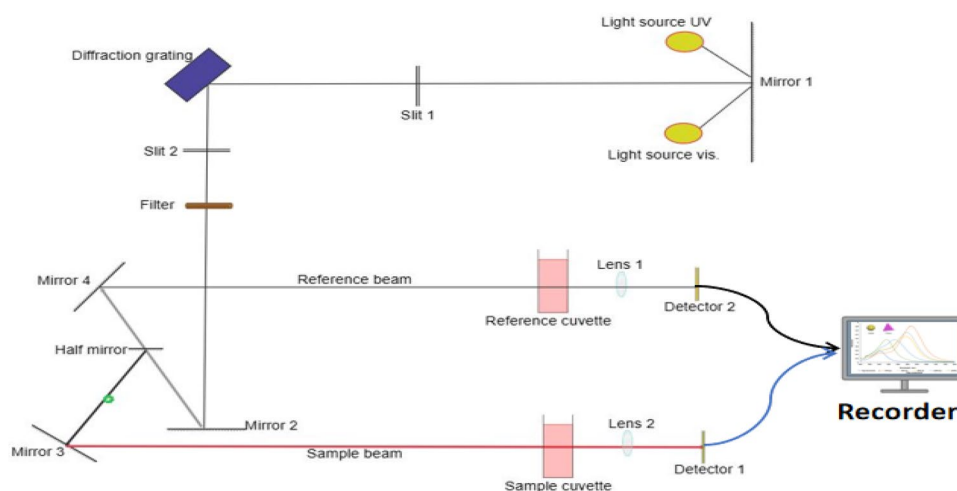
Infrared spectroscopy has long been an effective method for identifying organic compounds. FTIR spectroscopy has become a prominent tool for quantitative examination of complex mixtures, as well as the exploration of surface and interfacial phenomena [65]. IR spectrometer is a device that records both infrared spectroscopic and spatial information about a sample. Such images can reveal information about the sample's chemical and physical qualities [66].

Spectra of IR are determined by passing infrared rays through the sample and studying how much amount of incident rays are being absorbed at a particular frequency [67].

### 1.7 Mechanism of Corrosion Inhibition Process

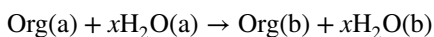
There exist various kinds of mechanisms on which inhibitors of corrosion work on metal surfaces; one of which is

**Fig. 6** Schematic diagram of working of UV–visible spectrophotometer



the adsorption mechanism. Generally, adsorption can be distinguished as physical adsorption, chemical adsorption, or mixed type; conditional on the interplay between metal and heteroatoms or  $\pi$ -electrons of the inhibitor [68]. Some defined parameters define the type of mechanism; including the chemical structure and charge distribution, and also metal surface charge. Chemical adsorption occurs by producing coordination bonds by a chemical reaction between unshared free pairs of electrons and unoccupied d-orbital of the metal and in physical adsorption, the charges on inhibitor molecules bind with electrically charged metal surface [69]. When one of the hydrogen atoms at the carbon atom in a heterocyclic ring is substituted by aldehyde, nitrosyl, carboxyl, or amino substituent groups; the inhibition efficiency of organic inhibitor increases [70].

In HCl, while introducing the organic compounds, they form a thin layer on metal and reduce the corrosion rate, called substitution reaction which takes place between inhibitor and water molecules at the metal-solution interface; which can be represented as:



where  $\text{Org}(a)$  and  $\text{Org}(b)$  are inhibitor molecules dissolved in solution and inhibitor molecules adsorbed on the metal surface, respectively, and  $\text{H}_2\text{O}(a)$  and  $\text{H}_2\text{O}(b)$  are water molecules and adsorbed water molecules on the metal surface, respectively.  $x$ , is the size ratio, representing the number of water molecules replaced by one molecule of organic inhibitor [71].

In addition, the membrane's stability of inhibitor molecules adsorbed on metal is based conditionally on active sites, steric hindrance, the electron density of molecules; acidic medium, and nature of the interaction between a  $\pi$ -orbital and d-orbitals of iron. Information regarding the adsorption mode of molecules on metal surfaces can be

achieved from the *adsorption isotherm* [28]. Different isotherms i.e. Langmuir (1), Flory–Huggins (2), Temkin (3) and Freundlich (4) explain the anti-corrosion mechanisms.

$$\text{Langmuir's isotherm} : \frac{C}{\theta} = \frac{1}{K_{ads}} + C \quad (1)$$

$$\text{Flory–Huggins isotherm} : \log \frac{C}{\theta} = \log(K_{ads}) + a \log C \quad (2)$$

$$\text{Temkin isotherm} : \theta = \frac{1}{f} \ln K_{ads} C \quad (3)$$

$$\text{Freundlich isotherm} : \log \theta = \log(K_{ads}) + n \log C \quad (4)$$

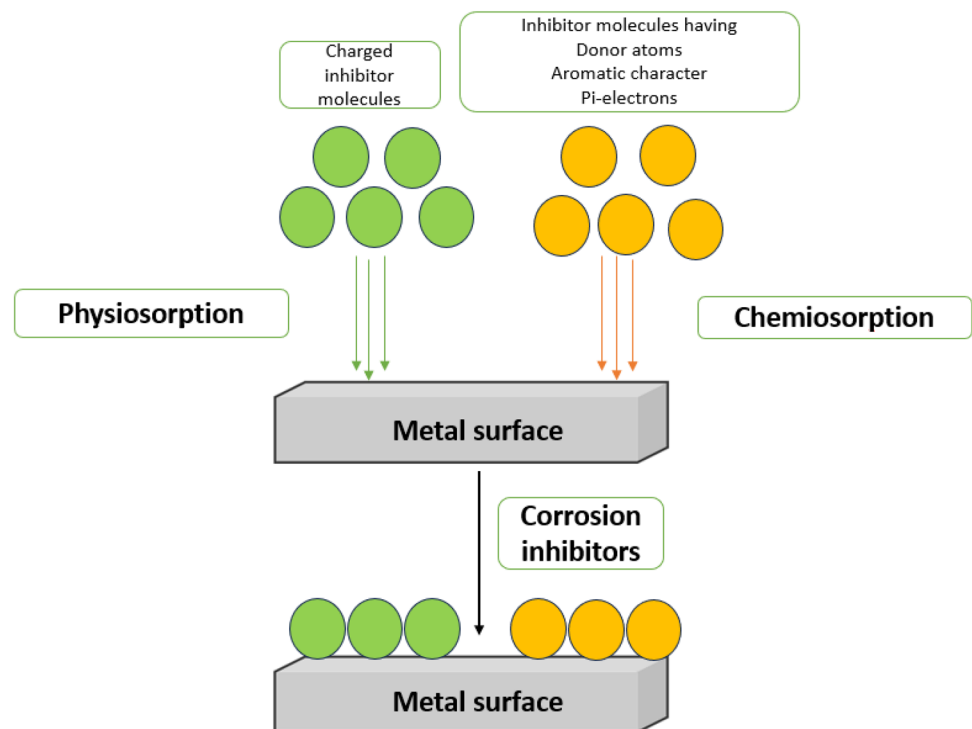
where  $C$  is the concentration of inhibitor in use,  $\theta$  is the degree of surface coverage,  $K_{ads}$  is constant,  $f$  is the energy parameter, and  $a$  is water molecules on the metal surface [72].

Figure 7 shows the mechanism of corrosion inhibition process in physical and chemical adsorption. The charged inhibitor molecules and inhibitor molecules having donor atoms aromatic character  $\pi$ -electrons are adsorbed on the metal surface. Chemisorption produces a coordination bonds in a chemical reaction whereas in physisorption, the charged inhibitor molecules bind up with the charge of the metal surface.

## 1.8 Current Research Status of Organic Corrosion Inhibitors

The research of organic corrosion inhibitors continues to be active and evolving. There is a growing emphasis on developing organic inhibitors that are environmentally friendly and sustainable. Researchers are exploring natural compounds, biodegradable polymers, and renewable resources

**Fig. 7** Mechanism of corrosion inhibition in physical and chemical adsorption



as potential inhibitors. Researchers are developing inhibitors tailored for specific applications and environments, including different types of metals, temperatures, pH levels, and corrosive agents. There is ongoing research into understanding the mechanisms by which organic inhibitors adsorb onto metal surfaces and inhibit corrosion. Organic corrosion inhibitors continue to be an active area of research aimed at enhancing corrosion protection, reducing maintenance costs, and extending the lifespan of metallic structures and equipment in various industrial sectors.

### 1.9 Future Scope of Corrosion Inhibition Studies

Corrosion inhibitors; are commonly used to stop or lessen corrosion in several domains, including industrial, construction, and cultural heritage. Conservation and restoration workers use corrosion inhibitors to protect and preserve metallic cultural material [73]. The future scope of corrosion inhibition research is promising; also affected by several components, including technical improvements, environmental concerns, also the changing needs of diverse businesses. Here are some potential areas of focus in the future:

- Advanced Materials and Nanotechnology
- Green Corrosion Inhibitors
- Smart Coatings and Sensors
- Computational Modelling and Simulation
- Corrosion in Renewable Energy Systems

### 1.10 Research Gap

As from the literature study most of the work done in HCl and H<sub>2</sub>SO<sub>4</sub>, but these compounds should also be studied in basic mediums and saline mediums. As apart from acidic medium, basic and saline conditions are also responsible for the corrosion of the metals.

## 2 Conclusion

The above studies about synthetic organic compounds reveal effective anti-corrosive properties that show significant potential in protecting various materials from corrosion. From various research and developments, these compounds show remarkable effectiveness in forming protective barriers or films, inhibiting reactions, and extending the lifespan of metal surfaces. Their versatility and compatibility with different substrates make them valuable assets in various industries. The compounds containing heteroatoms as active materials for being adsorbed on the surface of metal reducing metal dissolution in HCl or H<sub>2</sub>SO<sub>4</sub> medium. Each compound shows different inhibiting efficiency with different concentrations.

**Author Contributions** Anshula Sharma wrote the introduction and literature survey. Dr. Jasdeep Kaur compiled the methodologies that can be used to find the inhibition. Dr. Akhil Saxena reviewed the whole manuscript.



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**Data Availability** No datasets were generated or analyzed during the current study.

## Declarations

**Competing interests** The authors declare no competing interests.

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