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Carbon steel corrosion control using Schiff base inhibitors

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ABSTRACT

Corrosion represents a worldwide challenge, imposing an economic burden exceeding $2.5 trillion each year and impacting metal structures across diverse sectors. Corrosion inhibitors play a crucial role in alleviating metal corrosion and are widely utilized in the domain of corrosion protection, owing to their effectiveness, affordability, and eco-friendly characteristics. Schiff base (*Sb*) is characterized by their fundamental property of being suitable candidates for evaluation as corrosion inhibitors across various metal/electrolyte systems. *Sb* has the ability to adsorb and create a surface film that mitigates corrosion, facilitated by their electron-rich centers, particularly the > C = N– (imine) moiety that exhibits strong interactions with metallic ions. Typically, electron-donating substituents such as –OH (hydroxyl), $-CH_3$ (methyl), $-NH_2$ (amino), and $-OCH_3$ (methoxy) are believed to enhance the corrosion inhibition capabilities of *Sb*. This review article presents a compilation of information regarding corrosion phenomena of carbon steel (*CS*) and *Sb* as corrosion inhibitors. The interactions between *Sb* and *CS* surface at the molecular level are also addressed in this report. Furthermore, their associated inhibition mechanisms are elucidated through electrochemical techniques, surface characterization, adsorption isotherms, and theoretical analyses. In addition, this review aims to motivate researchers to explore the full potential of *Sb* as innovative *CS* corrosion inhibitor.

1. Introduction

1.1. Corrosion: Basics and economic influences

Corrosion process (*CP*) serves as the principal mechanism through which metals degrade. The majority of metals undergo corrosion upon interaction with water, as well as moisture present in the atmosphere), acids, bases, salts, oils, aggressive metal polishes, and various other solid and liquid chemicals. Furthermore, metals are prone to corrosion when subjected to gaseous substances, including acid vapors, formaldehyde, ammonia, and gases containing sulfur. *CP* is characterized as any process that leads to the deterioration or degradation of metallic components. *CP* is typically characterized by electrochemical reactions similar to those found in batteries [1–7].

This interaction leads to a decline in the material's properties. Specifically, in the context of electrochemical corrosion, it involves the breakdown of a material or its characteristics through electrochemical reactions between the electrically conductive material and its surrounding environment. The rate at which corrosion occurs is influenced by both the environmental conditions and the specific type of material involved. When metal atoms exposed to an environment rich in water molecules, they may release electrons, transforming into positively charged ions, provided that an electrical circuit is established. This phenomenon can manifest locally, resulting in pitting or cracking, leading to general material loss [8–12]. *CP* refers to the degradation of metal caused by chemical interactions with its environment. Pure metals are rarely encountered in nature; instead, they typically exist in chemical compounds with one or more non-metallic elements. These compounds are generally referred to as ore. A considerable amount of energy is required to convert ore into pure metal. This energy can be supplied through metallurgical or chemical processes, which occur during the operations known as smelting and refining [13–15]. *CP* is a natural phenomenon, which causes a huge disaster in industry and costs governments a lot of money. So, it's big problem in economy of countries. Millions of dollars are lost each year because of corrosion of iron and steel. The effect and cost of

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corrosion process can be elucidated as depicted in Fig.1. In economic terms, the substantial harm inflicted by the *CP* within the petroleum industry surpasses 3% of the Press Information Bureau (PIB) in the United States. The annual direct costs linked to metallic corrosion range from 2% to 4% of the gross domestic product (GDP) in developed countries, and this pattern is anticipated to rise in the coming years. [11,16,17].

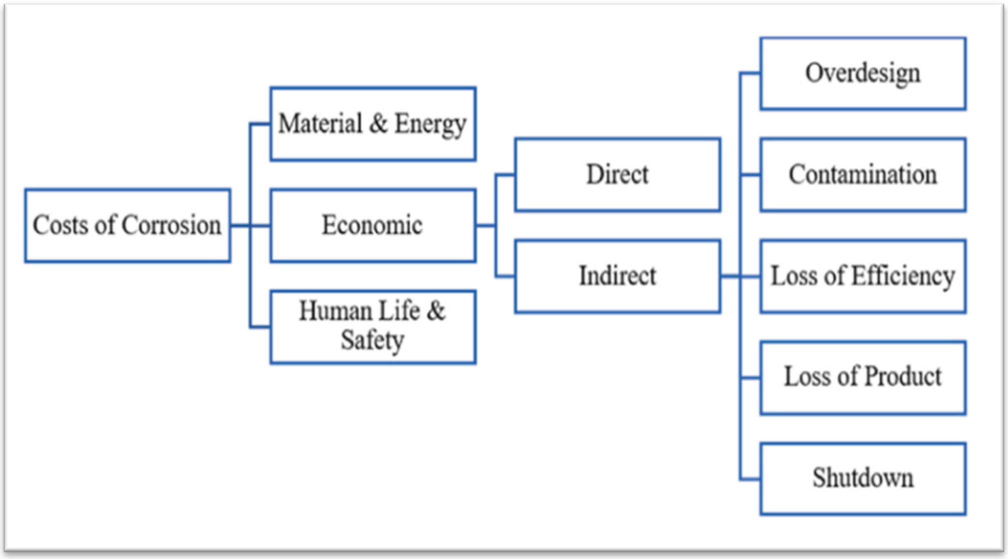


Fig.1: Effect of corrosion.

1.2. Chemistry of Corrosion

Generally, *CP* refers to the interaction between a metal and its surrounding environment, leading to alterations in the metal's properties that can be elucidated through the electrons sharing process. In electrochemical reactions, electrons are generated by a chemical reaction occurring in one region, known as the "anode," and subsequently travel to be utilized in a different chemical reaction in another region, referred to as the "cathode". *CP* necessitates the presence of three critical components: an electrolyte, an anode, and a cathode; the absence of any one of these elements inhibits the corrosion process [18–20]. The configuration of the anode, cathode, and electrolyte is known as a corrosion cell (Fig.2). An electrolyte is characterized as a solution that can conduct electrical current via the movement of ions. [21,22].

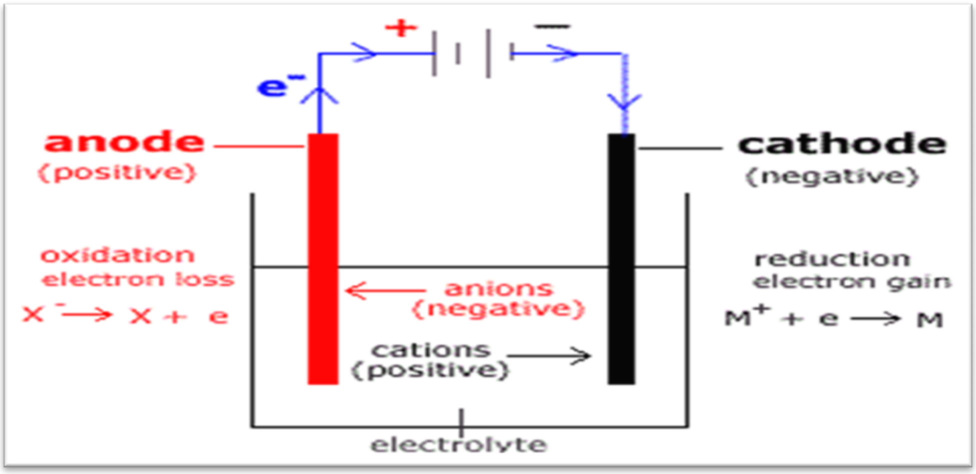


Fig.2: Electrochemical cell.

- ***Anodic reaction***

Anode is the positively charged electrode where electrons supply via the chemical activity of the metal and metal loss occurs in a process called oxidation. The anodic reaction involved in the corrosion process leads to the dissolution of metal as ions, which generates electrons that are subsequently utilized in a secondary process known as the cathodic reaction. It is essential for these two processes to maintain a charge balance. The locations of these reactions can either be in close proximity on the metal's surface or separated by a distance, depending on various factors. For instance, in the corrosion process of iron or *CS*, the reaction may unfold in two stages: initially, iron is oxidized to form ferrous ions. Subsequently, these ferrous ions may be further oxidized to ferric ions, contingent upon the electrochemical potential [23,24]. The deposition of these ions on the metal surface is influenced by environmental conditions, leading to the formation of iron hydroxide, commonly known as “rust,” which is frequently observed on various industrial and civil structures. Ultimately, depending on the environmental conditions, the metal may completely dissolve; however, in most industrial applications involving steel, this can lead to structural failures in equipment such as pipelines or machinery [25].

Anodic chemical formula: $M \rightarrow M^{+} + e^{-}$

here, M, M^{+}, and e^{-} are uncharged metal surface, positively charged metal, and electrons respectively. This process is referred to as an oxidation reaction, despite the fact that it does not directly engage oxygen; rather, it leads to a rise in the positive charge of the atom that is experiencing oxidation. For example: in case of iron, more than one electron can be lost where the most common anodic reaction is:

$$Fe \longrightarrow Fe^{2+} + 2e$$

- ***Cathodic Reaction***

In an electrochemical cell, the cathode is the negatively charged electrode. Cathode is the site where electrons are consumed through reduction process and no metal loss occurs. The anodic reactions described above must be counterbalanced by reduction processes that take place at the cathode. Specifically, the electrons generated at the anode through oxidation must be utilized in a reduction reaction at the cathode. It is important to note that anodes and cathodes can consist of either two distinct metal pieces or different locations on a heterogeneous surface of a single metal piece [26,27]. In an acidic solution, the predominant cathodic reaction is the evolution of hydrogen. Conversely, in an alkaline aqueous solution, this reaction can be represented differently. When dissolved oxygen is present. In an acidic environment, this reaction proceeds as follows, while in an alkaline environment, it occurs as indicated [28]. Additionally, there are several other potential partial cathodic corrosion reactions, although their occurrence is contingent upon the specific chemistry of the electrolyte.

Cathodic chemical formula: $M^{+} + e^{-} \rightarrow M$

In an environment containg with water is:

$$O_2 + 2H_2O + 4e^{-} \longrightarrow 4OH^{-}$$

So, the final reaction leads to iron oxides formation as follow:

$$Fe^{2+} + 2\,OH \longrightarrow Fe(OH)_2$$

Finally, $Fe(OH)_2$ will subsequently undergo a reaction to produce Fe_2O_3 and Fe_3O_4, commonly known as rust.

- ***Electrolyte***

An electrolyte is defined as a substance that generates an electrically conductive solution upon dissolution in a polar solvent, like water. When the electrolyte dissolves, it dissociates into cations and anions that distribute evenly throughout the solvent. When electrodes are immersed in the electrolyte and a voltage is applied, the electrolyte facilitates the conduction of electricity. A chemical reaction transpires at the cathode, supplying electrons to the electrolyte. Conversely, another reaction takes place at the anode, where electrons are consumed from the electrolyte. Consequently, a cloud of negative charge forms in the electrolyte surrounding the cathode, while a positive charge accumulates around the anode [29,30].

1.3. Different types of corrosion

Several corrosion forms are categorized according to their appearance as seen in Fig.3. The main forms of corrosion are follows.

1.3.1. Uniform (or general) corrosion:

This phenomenon is characterized by a consistent destructive action that affects the entire surface area or a substantial portion of it uniformly. The process leads to a general reduction in thickness until structural failure occurs. In terms of material degradation, this represents the most significant type of corrosion. Additionally, uniform corrosion is easy to measure and predict. It is often considered problematic mainly from an aesthetic standpoint [31,32].

1.3.2. Pitting corrosion:

Pitting corrosion is a localized type of corrosion that results in the formation of cavities or 'holes' within the material. It poses a greater risk than uniform corrosion damage due to its challenging detection, unpredictability, and the difficulty in designing preventive measures. Additionally, corrosion products frequently obscure the pits [33,34].

1.3.3. Crevice corrosion:

Localized corrosion is typically linked to stagnant solutions at the microenvironmental level. These stagnant conditions often arise in crevices, which are shielded areas found beneath gaskets, washers, fastener heads, surface deposits, threads, and clamps. Due to the limited diffusion of oxygen into these crevices, a variance aeration cell is likely to develop between the microenvironment within the crevice and the surrounding bulk environment [35–37].

1.3.4. Galvanic corrosion:

CP occurs when various metallic substances interact with one another in the presence of an electrolyte. This type of degradation may also occur among metals, alloys, and various conductive substances like carbon or graphite through the varying in corrosion potentials. The material exhibiting a more noble corrosion potential acts as the cathode of the corrosion cell, while the material with a less noble potential undergoes anodic dissolution. [38].

1.3.5. Intergranular corrosion:

Localized corrosion manifests at the boundaries of grains or in their close proximity, whereas most of the grains remain largely unscathed. Intergranular corrosion is frequently associated with the impacts of chemical segregation, wherein impurities are prone to gather at the grain boundaries, or with particular phases that crystallize at these boundaries. Such crystallization can lead to the formation of regions with reduced corrosion resistance in the vicinity as in stainless steels [39].

1.3.6. Fretting corrosion:

The *CP* leads to the appearance of metal surface with pits and grooves. Fretting corrosion arises from the repeated application of weight, and/or vibration on a rough surface. This type of corrosion is commonly observed in rotating and impact machinery, bolted assemblies, and bearings, as well as on surfaces subjected to vibration during transport. [40].

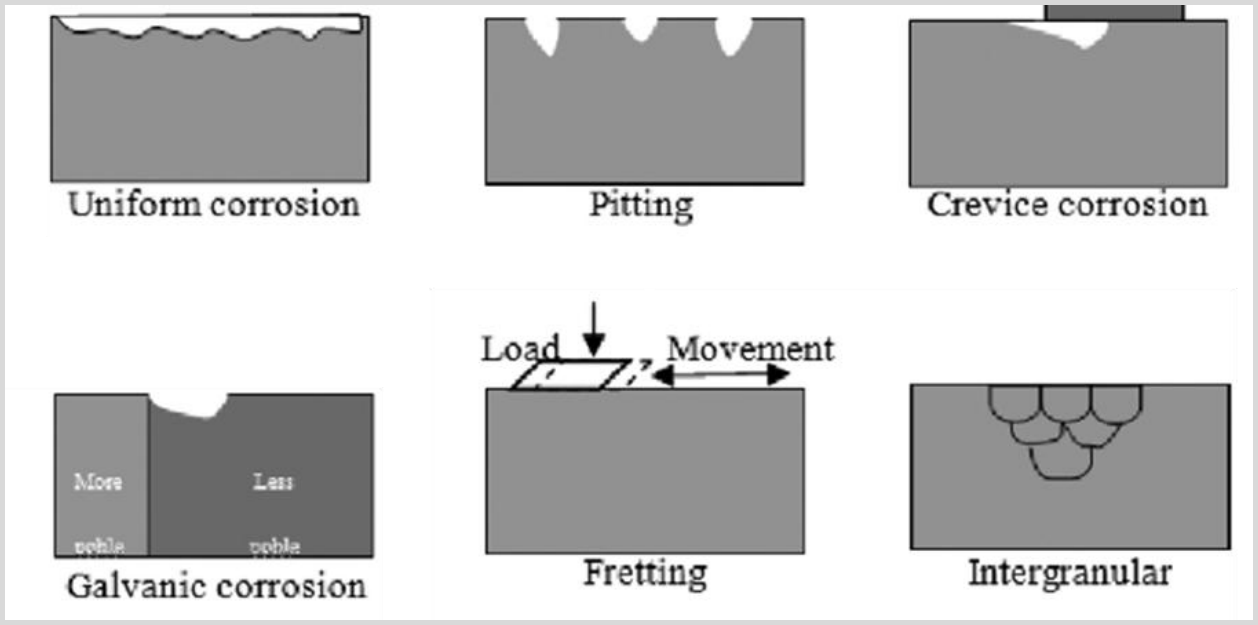


Fig.3: Various types of corrosion.

2. Carbon steel

Carbon steel (*CS*) represents a crucial category of engineering alloys, with a substantial proportion of steel production being *CS*, which is a metal alloy composed primarily of two elements: iron and carbon. Other elements, such as manganese, silicon, and copper, are present in minimal amounts that do not significantly influence its properties[17,41–43]. The application of *CS* across diverse industrial sectors, like automobiles, machine components, bridges, and petroleum industry [41–43]. *CS* with a low carbon content exhibits similar characteristics to iron, being soft and easily shaped; however, as the carbon content increases, the metal acquires greater hardness and strength, while becoming less ductile and more challenging to weld. An increase in carbon content also results in a reduction of the melting point of steel and its overall temperature resistance [44–46].

2.1. Carbon steel types

Carbon steel is broken down into four classes based on carbon content as follow:

- ***Low carbon steel (Mild steel)***

Low-*CS* is characterized by a low carbon content, is a prevalent type of steel due to its affordability and satisfactory material properties for various applications. This type of steel typically contains around 0.05–0.30% carbon, which contributes to its malleability and ductility. Although mild steel exhibits lower tensile strength, it is cost-effective and easily shaped. The surface hardness of mild steel can be enhanced through the process of carburization. Low-carbon or mild carbon steels are favored for their excellent welding and forming capabilities, rendering them highly appealing for construction purposes. However, these carbon steels are prone to corrosion, particularly from atmospheric exposure. [20]**.**

- ***Medium-carbon steel***

Medium-*CS* contains roughly 0.3–0.5% carbon content. This composition provides a balance between ductility and strength, along with commendable wear resistance. It is commonly utilized in the production of large components, forging processes, and automotive parts. [44].

- ***High-carbon steel***

High-*CS* contains around 0.6 to 1.0% carbon, making it exceptionally strong and suitable for applications such as springs, cutting tools, and high-strength wires [20]**.**

- ***Ultra-high-carbon steel***

Ultra-high- *CS* comprises approximately 1.25 to 2.0% carbon content. This category of steel can be tempered to attain considerable hardness and is employed in specialized applications such as non-industrial knives, axles, and punches. Generally, steels with carbon content surpassing 2.5% are manufactured using powder metallurgy methods. A significant drawback of these alloys is their noticeable vulnerability when subjected to prolonged exposure to aqueous environments. This is attributed to the development of pockets and/or crevices that can trap moisture and water accelerating corrosion attack, leading to corrosion failure and loss of properties [45].

3. Corrosion inhibitors

Despite the extensive application of *CS*, it is currently facing challenges due to the corrosion process (Fig.4) that occurs particularly in the petroleum industry during cleaning and descaling operations. Consequently, researchers have concentrated their efforts on identifying an effective and cost-efficient method for the protection of *CS*, aiming to mitigate the substantial expenses associated with corrosion in diverse aggressive environments, including nitrate, sulfate, and chloride solutions. Recently, organic compounds have gained prominence as corrosion inhibitors (*CIs*) due to their exceptional protective characteristics [3,46]. The *CIs* refer to any chemical substance that, when introduced into a corrosive environment (typically in minimal quantities), reduces the effects of the environment on the degradation of metal [47,48]**.** For an inhibitor to achieve success, it must effectively remove water molecules from the corrosion substrate (*CS*) surface and obstruct corrosion sites. This action leads to alterations in electrochemical reactions, thereby enhancing corrosion resistance. The effectiveness of *CIs* is largely due to their ability to adsorb onto a metal surface, forming a protective layer [13–15].

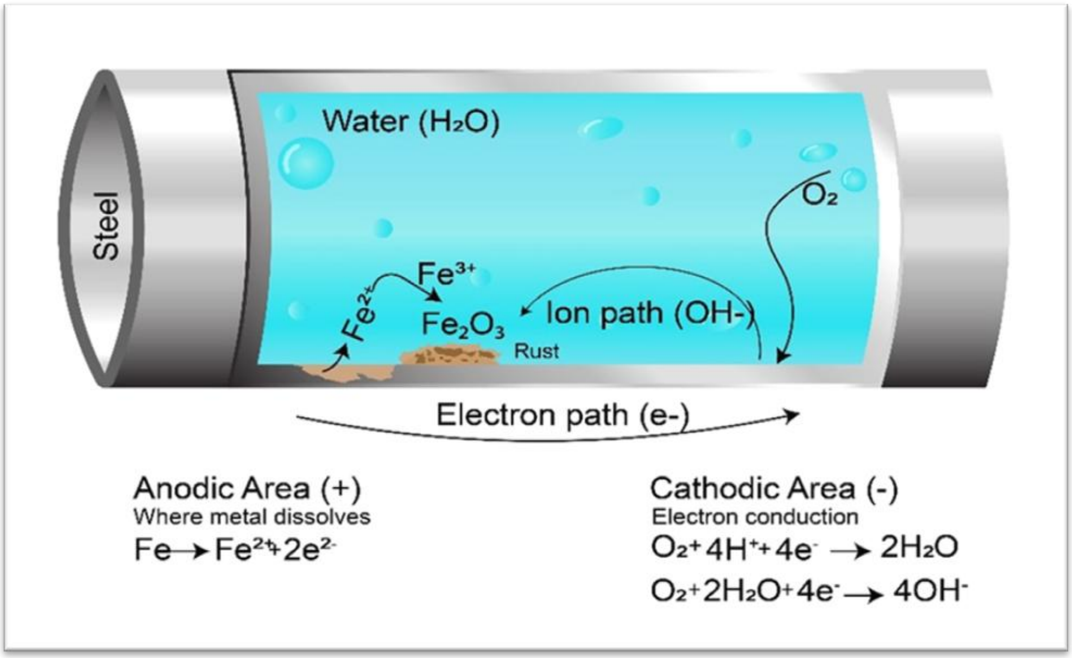


Fig.4: Corrosion process of carbon steel.

3.1. Structure of the Inhibitor

Inhibitors can establish a coordinate bond with the metal through electron transfer. Inorganic compounds that contain functional groups with elements from groups V and VI of the periodic table possess suitable lone pairs of electrons for coordinate bonding. The propensity for stronger coordinate bond formation, and consequently enhanced adsorption due to the existence of hetero atoms as (O, N, and S). Additionally, this tendency is influenced by the characteristics of the functional group which are generally believed to enhance the inhibitor's efficacy as it rises forming coordinate bond with the metal surface is formed, resulting in greater adsorption [49,50]**.**

3.2. Classification of inhibitors

Inhibitors can be classified as follow:

- ***Anodic inhibitors***

Passivating inhibitors, also known as passivators or anodic inhibitors, are a category of substances that function by obstructing the anodic reaction. These inhibitors integrate into the oxide layer on the metal surface, thereby enhancing its stability and preventing further corrosion. Although the metal's appearance typically remains unchanged, it is covered by a very thin film that can be detected using specialized techniques.. These inhibitors are recognized for their high efficacy and widespread application. However, if the concentration of anodic inhibitors is inadequate, corrosion may be exacerbated instead of mitigated. The threshold concentration at which these inhibitors become effective is contingent upon the type and concentration of the aggressive ions present [51].

- ***Cathodic inhibitors***

Cathodic inhibitors impede the cathodic reaction by either limiting oxygen access or by contaminating sites conducive to cathodic hydrogen evolution. Among the cathodic inhibitors that mitigate the corrosive effects of aqueous solutions on steel are the salts of magnesium, manganese, zinc, and nickel. The reduction of oxygen to hydroxide ions (OH^-) increases alkalinity near the vessel walls, resulting in the precipitation of metal hydroxides as a relatively adherent porous layer that hinders oxygen diffusion to the steel surface. When calcium carbonate is present in water, it can precipitate as a general calcium carbonate deposit if the water is supersaturated, or it may form localized deposits in cathodic regions where the pH is elevated. The introduction of lime into water raises the pH and acts as a cathodic inhibitor. Although cathodic inhibitors that create a visible film on metal surfaces are generally less effective than anodic inhibitors and do not entirely prevent corrosion, they are less likely to exacerbate corrosion when applied in adequate quantities [52].

- ***Mixed inhibitors***

Inhibitors that induce precipitation are compounds that form films with a general effect on the metal surface. Silicates and phosphates are among the most dominant inhibitors in this category. Conversely, organic inhibitors typically consist of organic compounds that adsorb across the entire metal surface, simultaneously slowing down both anodic and cathodic reactions. These inhibitors retard the *CP* of *CS* via film construction which protects its surface by establishing a covering hydrophobic layer [53,54].

4. Corrosion measurements techniques

4.1. Weight loss (WL)

The analysis of weight loss (WL) represents the most straightforward among all available corrosion testing techniques and has been the most established method for measuring corrosion in industrial plants and equipment. To obtain pertinent corrosion data through weight loss methods, it is essential to consider various factors, including the purpose of the test, physical parameters, and duration of exposure. The primary steps that must be meticulously followed during corrosion measurement using this technique include specimen preparation, initial cleaning, immersion in the testing medium, removal of corrosion products, and assessment of the results obtained. The corresponding corrosion rate (r, mg cm^{-2} h^{-1}) and the inhibition efficiency (η_{W_L}) were estimated via the following equations [55]:

$$r = \Delta W / At \qquad (1)$$

$$\eta_{W_L} = \frac{W_{HCl} - W_i}{W_{HCl}} \times 100 \qquad (2)$$

where; t, A, W_i and W_{HCl} denote immersion time (h), exposed *CS* surface area (cm^2), and W_i and W_{HCl} represent the mass change with and without inhibitors respectively.

4.2. Potentiodynamic polarization (PDP)

Potentiodynamic polarization (PDP) is an electrochemical method employed to investigate the corrosion behavior of materials by altering the electrode potential and recording the resultant current. This technique is instrumental in elucidating corrosion mechanisms, rates, and characteristics, thereby proving essential for surface engineering and materials science. The process entails applying a potential sweep to a sample material and measuring the associated direct current to assess its corrosion resistance and behavior. Also, PDP provides several corrosion parameters as anodic and cathodic Tafel slopes (β_a and β_c), corrosion potential (E_{corr}), and corrosion current density (i_{corr}) from the extrapolation of Tafel slope. The inhibition efficiency can be calculated based on (i_{corr}) as follow [56]:

$$\eta_{PDP} = \left(\frac{\mathrm{i}_{blank} - \mathrm{i}_{inh}}{\mathrm{i}_{blank}}\right) x\ 100 \qquad (3)$$

where, i_{blank} and $i_{inh.}$ are corrosion current densities for blank solution and inhibitor respectively.

4.3. Electrochemical impedance spectroscopy (EIS).

Electrochemical Impedance Spectroscopy (EIS) is an exceptionally sensitive technique employed to assess the electrical response of electrochemical systems, including corrosion, without causing any damage. Through the EIS method, the kinetics that take place at the interface between steel and the solution can be examined in detail using a non-destructive and quasi-steady state approach. The effectiveness of corrosion inhibitor was investigated utilizing the highly accurate EIS technique to gain further insights into the electrical response of the corrosion process, employing alternating current (AC) within a frequency range that induces electrochemical reactions at the working electrode surface. EIS provides several indices for the corrosive system as R_s (solution resistance), *CPE* (constant phase element) which can be defined by Y^o and coefficient n and R_p (polarization resistance). The inhibition efficiency can be calculated based on R_p as follow:

$$\eta_{EIS} = \left(\frac{R_{P.inh} - R_{P.blank}}{R_{P.inh}}\right) \times 100 \qquad (4)$$

where, $R_{P.blank}$ and $R_{P.inh}$ are the polarization resistance for the examined metal in absence and presence of inhibitor respectively [57]

4.4. Surface analyses

Several surface examinations can be applied for electrode surface evaluation as Scanning Electron Microscope (SEM), EDX (Energy Dispersive X-ray), AFM (Atomic Force Microscope), and X-ray Photoelectron Spectroscopy (XPS). SEM serves as an essential instrument for the analysis of corrosion as 2D image. It delivers high-resolution images of corroded surfaces, which disclose intricate details regarding the morphology of corrosion products, the degree of damage, and the underlying mechanisms at play. Additionally, SEM can be utilized alongside EDX to ascertain the elemental composition of corrosion products, thereby enhancing the comprehension of the corrosion process. SEM images obtained at high magnification offer a potent and efficient technique for corrosion studies [58]. AFM has been employed in the study of corrosion inhibition, in conjunction with various other techniques, to examine the surface morphology of the protective film at the nanometer scale as 3D image. The average roughness, root-mean-square roughness, and maximum peak-to-valley (P-V) height values provide a visual representation of the protective film at the nanoscale [59]. Also, XPS is an effective surface-sensitive method employed to investigate corrosion through the examination of the elemental composition and chemical states of materials, especially within the upper 1-10 nm of a surface. This technique aids in comprehending corrosion mechanisms, recognizing corrosion products, and evaluating the efficacy of protective coatings by scrutinizing the binding energies of these electrons, XPS is capable of identifying the elements and their respective oxidation states [60].

5. *Schiff base inhibitor*

In recent decades, the focus of researchers has shifted towards the discovery of new effective, non-toxic, and ecofriendly *CIs* the *CS* protection, as Schiff-base (*Sb*) that are familiar with their high inhibition competence. *Sb* can be prepared through the reaction of aldehyde with an amine or a ketone (condensation reaction), exhibiting greater inhibition potency compared to their corresponding aldehydes and amines due to the presence of the $NR=R_2C$ group, as illustrated in Fig.5 [61,62]. The application of nitrogen-containing inhibitors, including *Sb* and its derivatives, may effectively hinder the *CP* by creating a barrier film onto the metal surface that prevents ionic attacks from reaching the surface through the adsorption process. The inhibition ability of *Sb* can be explained by formation of complexes through N-atom, besides existence of C=N which enhances the adsorption capacity, thereby reducing the corrosion rate [63]. The majority of *Sb* inhibitors, which establish robust coordinate bonds with metal ions, are synthesized from alkyl diamines and aromatic aldehydes. Also, a comparative analysis between different Schiff base inhibitors for carbon steel was summarized as seen in Table 1.

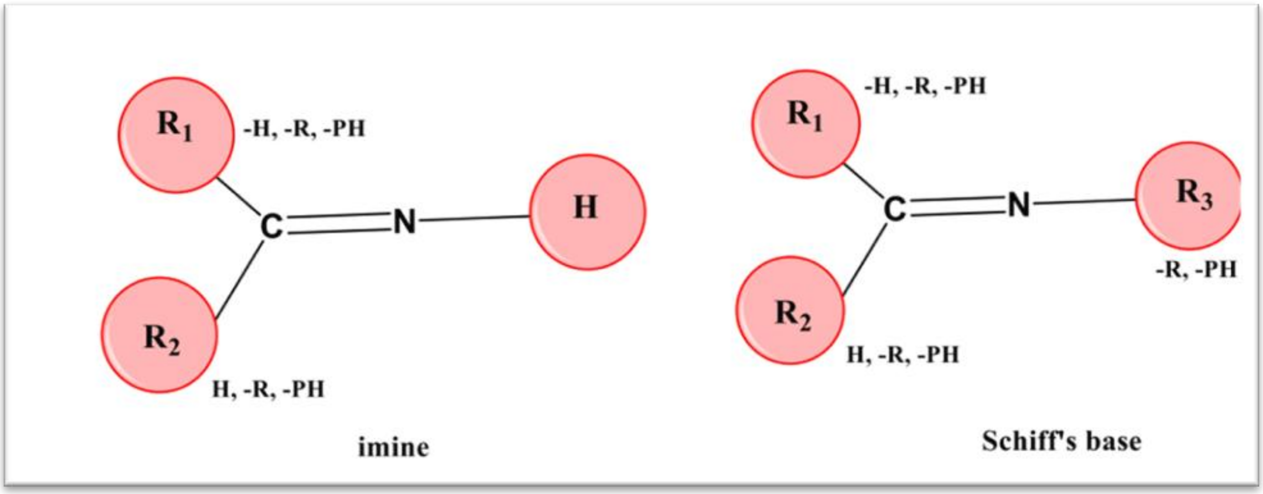


Fig.5: Basic structure of imine and Schiff base.

Table 1: The inhibition efficiency of some published *Sb* inhibitors for *CS* using PDP and EIS.

Inh.	*Conc.*	*EIS*	*PDP*	Reference
		η%	*η%*	
1	2×10^{-3}	85.4	81.9	[64]
Imine-NO₂	1×10^{-3}	89.1	90.0	[22]
EEMD	1×10^{-3}	87.0	88.1	
INB	1×10^{-3}	91.1	90.2	[65]
IMB	1×10^{-3}	91.9	91.5	
L3	1×10^{-3}	76.83	75.5	[66]
4-PCPTC	1×10^{-3}	89	89	[67]
SB-CH₃	1×10^{-3}	89.44	89.19	[68]
SB–OCH₃		90.30	89.31	
S1H	5×10^{-3}	----	91	[69]
Isonitrosoacetanilide	5×10^{-3}	79.3	75.7	[70]
S4	1×10^{-2}	92.6	92.2	[71]
Di-Sb	1×10^{-3}	93.027	92.95	[43]

5.1. *Schiff bases as corrosion inhibitors: Literature survey.*

A variety of *CIs* were examined to diminish the metal corrosion rate in diverse destructive settings. The primary aim of our study is to advance a cost-effective, environmentally friendly, and easily produced effective inhibitor that incorporates heteroatoms and π-bonds.

These features enhance the interaction between the inhibitor's adsorption center and the vacant d-orbital of iron, thereby creating a protective insulation film that effectively reduces *CP* of carbon steel, even at minimal doses [64,67,72,73].

Mohammed Mustafa et.al [25] examined the behavior of eco-friendly Isatin/Chitosan inhibitor (Isatin-Cs) for Q235-*CS* in 1.0 M HCl as depicted in Fig.6 utilizing gravimetric weight loss at various temperature levels, potentiodynamic polarization (*PDP*), and electrochemical impedance spectroscopy (*EIS*). The examined Isatin-Cs mitigated Q235-*CS* effectively by formation of an insulation layer shielding Q235-*CS* with inhibition efficacy 92.2 % using *PDP* at 250 ppm. Also, scanning electron microscopy (SEM) supported with X-ray photoelectron spectroscopy (XPS) and water contact angle methods were applied to Q235-*CS* surface examination.

Merfat S. Al-Sharif [24] conducted a study on the efficacy of two Schiff bases (INB and IMB) as corrosion mitigators for *CS* in 0.5 M sulfuric acid solution via electrochemical and computational assessment, as illustrated in Fig.7 exhibiting *PDP* and *EIS* techniques. The results indicated that INB and IMB displayed significant anticorrosive properties in a 0.5 M H2SO4 environment, with the inhibition efficiency of the 10^{-3} M IMB inhibitor reaching 92%. Through simulations utilizing density functional theory (DFT) supported with molecular dynamics simulations (MDs), the molecular structures of INB and

IMB, along with their impact on the inhibition mechanism, were analyzed. The DFT/MDs computational studies revealed a robust correlation between the theoretical predictions and the experimental findings.

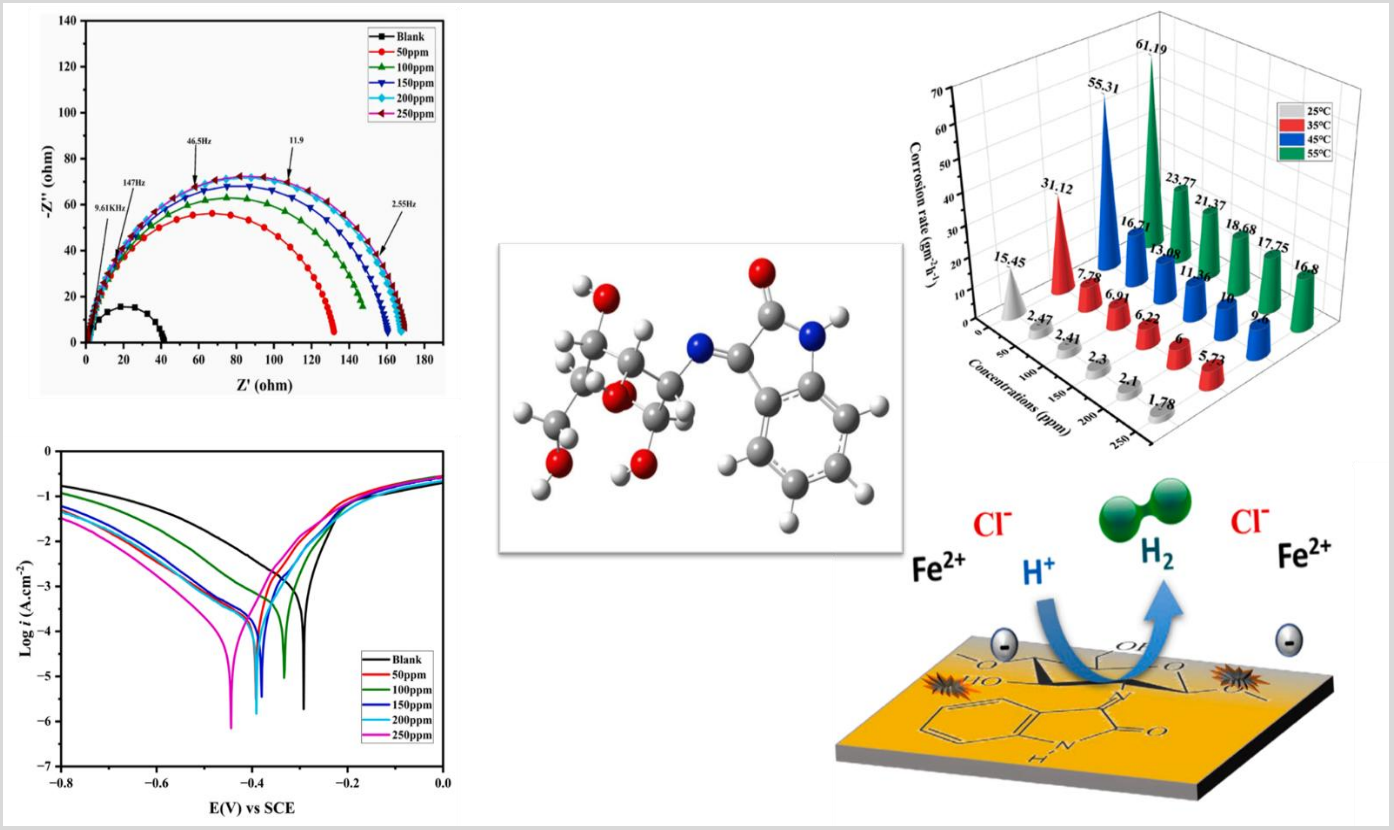


Fig.6: Weight loss, *PDP*, and *EIS* of *Isatin-Cs* in acidic 1 M HCl solution.

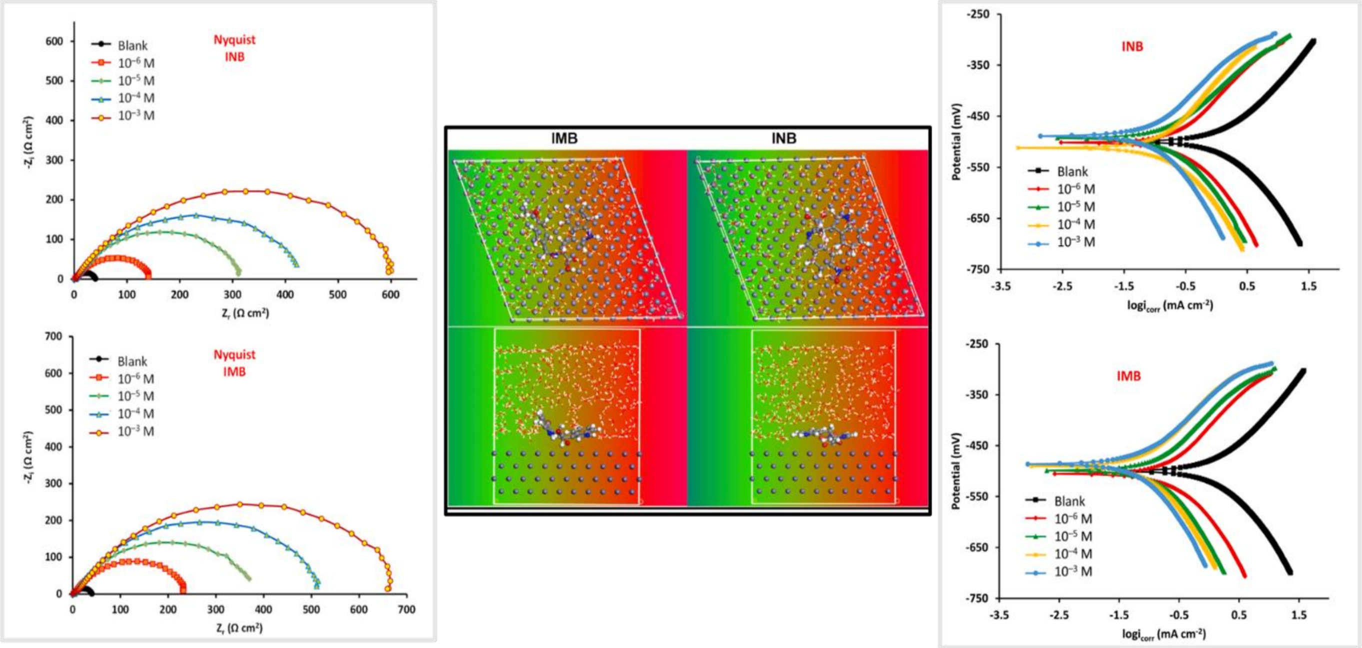


Fig.7: *PDP*, *EIS*, and *MDs* of *INB* and *IMB* in in 0.5 M sulfuric acid solution.

Z. Amrani et.al [22] evaluated two analogs of Bis-Schiff bases (*Imine-NO$_2$* and *EEMD*) as anti-corrosion *CS* agents in 1 M HCl through a variety of theoretical and experimental methodologies (Fig.8), such as quantum theory modeling, PDP, EIS, and surface analysis via SEM-EDS. The results from PDP indicated that *Imine-NO$_2$*and

EEMD exhibited a synergistic inhibition effect on *CS*, reaching a maximum of 93% for *EEMD* and 89.6% for *Imine-*NO_2. This phenomenon can be elucidated by *Imine-*NO_2 and *EEMD* adsorption on the *CS* surface through chemisorption processes that conform to the Langmuir adsorption model. DFT was employed to investigate the *Imine-*NO_2 and *EEMD* electronic structure, thereby enhancing and validating the experimental findings. Bis-Schiff bases demonstrate significant inhibition of *CS* corrosion, with their efficacy being dependent on concentration and temperature, following the hierarchy: *Imine-*NO_2 > *EEMD*. This can be elucidated by the existence of an additional -CH-OH group in *Imine-*NO_2, which amplifies its effectiveness.

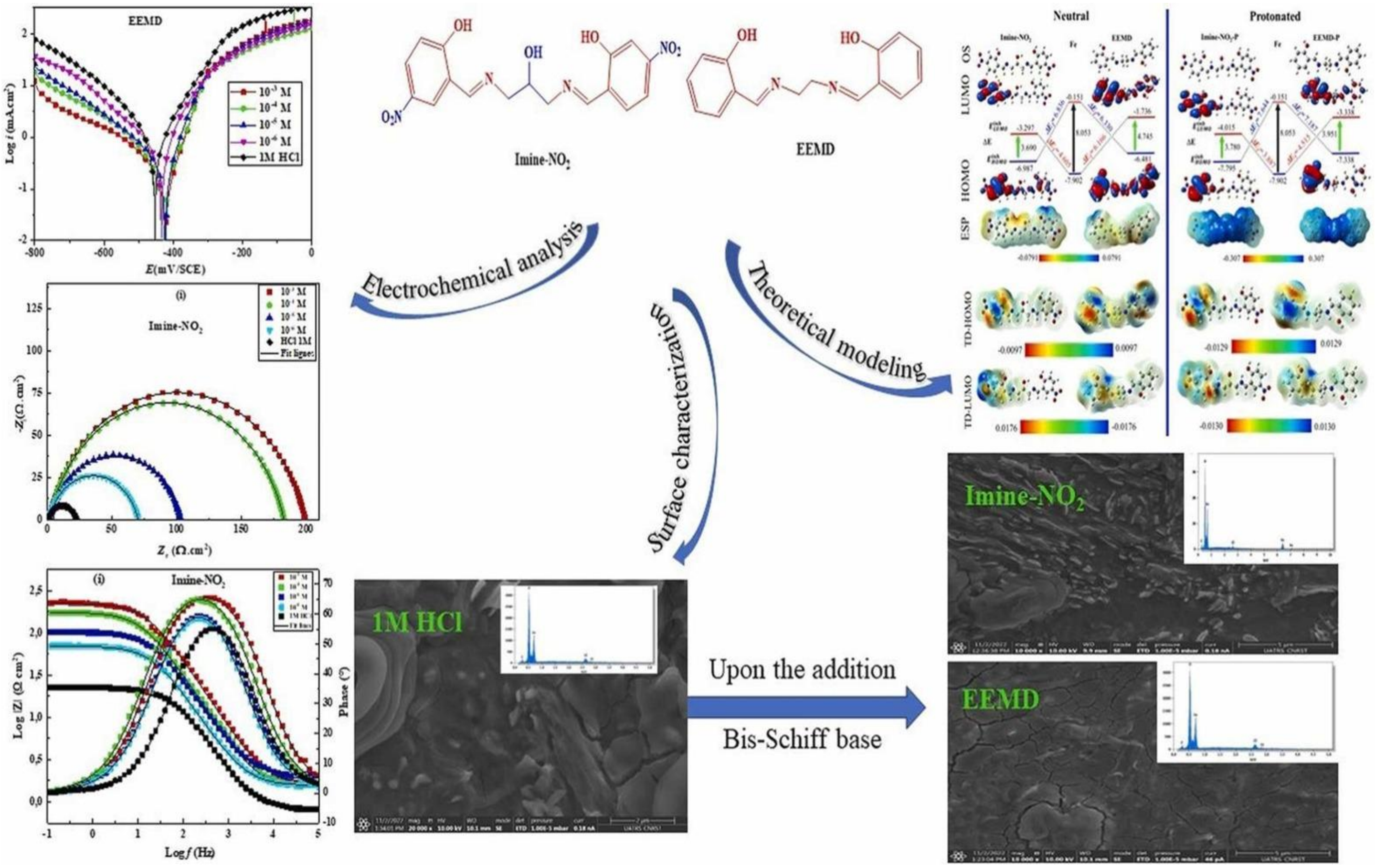


Fig.8: *PDP*, *EIS*, *SEM*, and *DFT* of *Imine-*NO_2 and *EEMD* in 1 M HCl solution.

MM. Salim et.al [68] studied *ρ*-substituted imine mitigators coded (*SB–*OCH_3 and *SB-*CH_3) as corrosion mitigators for *CS* in 1 M HCl solution via weight loss, *EIS*, and *PDP* methods as in Fig.9. The examined *SB–*OCH_3 and *SB-*CH_3 retarded *CS* corrosion reactions (anodic and cathodic) reflecting their mixed inhibition performance. *EIS* data bolstered the defense of *CS* surface through the formation of resistant adsorbed layer of *SB–*OCH_3 and *SB-*CH_3 that obeyed Langmuir adsorption isotherm. Additionally, the adsorption mechanism *SB–*OCH_3 and *SB-*CH_3 onto *CS* surface was evaluated employing theoretical calculations (DFT and MCs). Also, *CS* surface examination proved the defensive role of *SB–*OCH_3 for *CS*. Additionally, the fabricated *SB–*OCH_3 and *SB-*CH_3 declined *CS* reaction with mitigation efficacy more than 90%.

Hojat Jafari, and Elham Ameri [74] investigated the inhibition capacity of CHNO inhibitor for *CS* in 1 M HCl electrolyte. The CHNO protection ability was assessed via EIS, PDP, and Atomic Force microscopy (AFM) method as depicted in Fig.10. Also, based on the obtained findings, the thermodynamics parameters were calculated for *CS* corrosion in both the absence and presence of CHNO. The test results indicated that CHNO exhibited effective performance as corrosion inhibitor, with the inhibition percentage of steel corrosion increasing alongside the concentration, ultimately reaching 70% at a concentration of 2×10^{-3} M. PDP tests revealed that CHNO functions as a mixed inhibitor, besides, EIS demonstrated that CHNO introduction into the solution enhanced the charge transfer resistance while reducing the double layer capacity. The adsorption of CHNO onto *CS* obeys Langmuir adsorption isotherm, and the calculated free energy of adsorption suggested that CHNO adsorption was spontaneous. Furthermore, AFM investigations corroborated the findings obtained from the electrochemical methods.

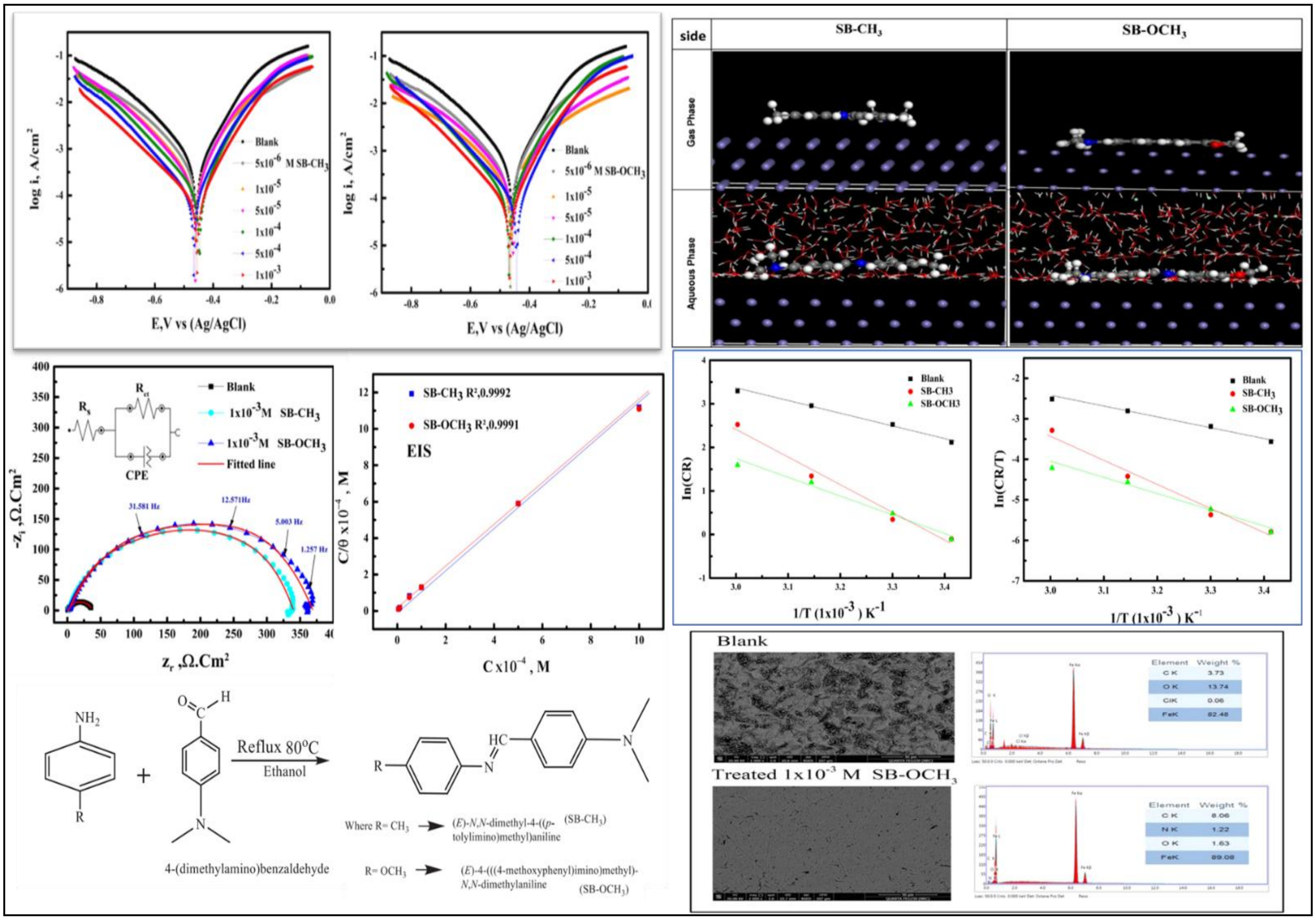
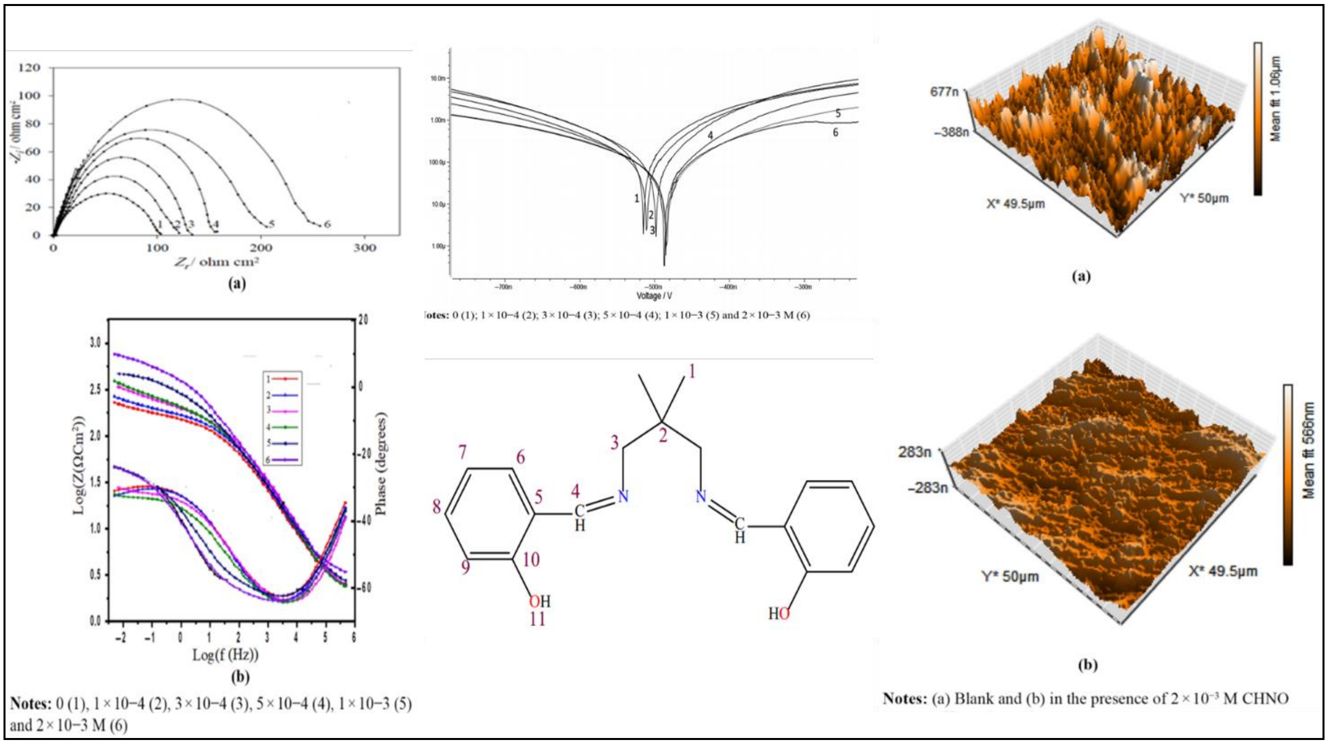


Fig.9: *PDP*, *EIS*, *SEM*, *EDS*, Langmuir isotherm, Arrhenius, Transition state, and *MCs* of *SB–OCH₃* and *SB-CH₃* in 1 M HCl solution.



Notes: 0 (1), 1 × 10−4 (2), 3 × 10−4 (3), 5 × 10−4 (4), 1 × 10−3 (5) and 2 × 10−3 M (6)

Notes: 0 (1), 1 × 10−4 (2), 3 × 10−4 (3), 5 × 10−4 (4), 1 × 10−3 (5) and 2 × 10−3 M (6)

Notes: (a) Blank and (b) in the presence of 2 × 10⁻³ M CHNO

Fig.10: *PDP*, *EIS*, and AFM, of CHNO in 1 M HCl solution.

Amal R. El Tohamy et.al [75] studied the *CS* corrosion n a water-based environment (HCl) before and after injection of SB-inhibitor utilizing PDP, EIS, and WL measurements as in Fig.11. The corrosion behavior was assessed within the temperature range of 298-333 K, both in the presence and absence of the SB-inhibitor. The inhibitory effectiveness of SB-inhibitor was 84.0% at 298 K. The changes in kinetic and thermodynamic properties of SB-inhibitor on *CS* suggested a mixed adsorption mechanism (physisorption and chemisorption). The PDP curves demonstrated SB-inhibitor mixed inhibition activity, which aligns with the Langmuir adsorption isotherm. The experimental findings are corroborated by DFT and MCs, highlighting the potential of SB-inhibitor in *CS* corrosion control in acidic conditions. SEM and EDX analyses showed the formation and adsorption of a continuous layer of SB-inhibitor molecules over *CS*. which validated SB-inhibitor effectiveness as an inhibitor.

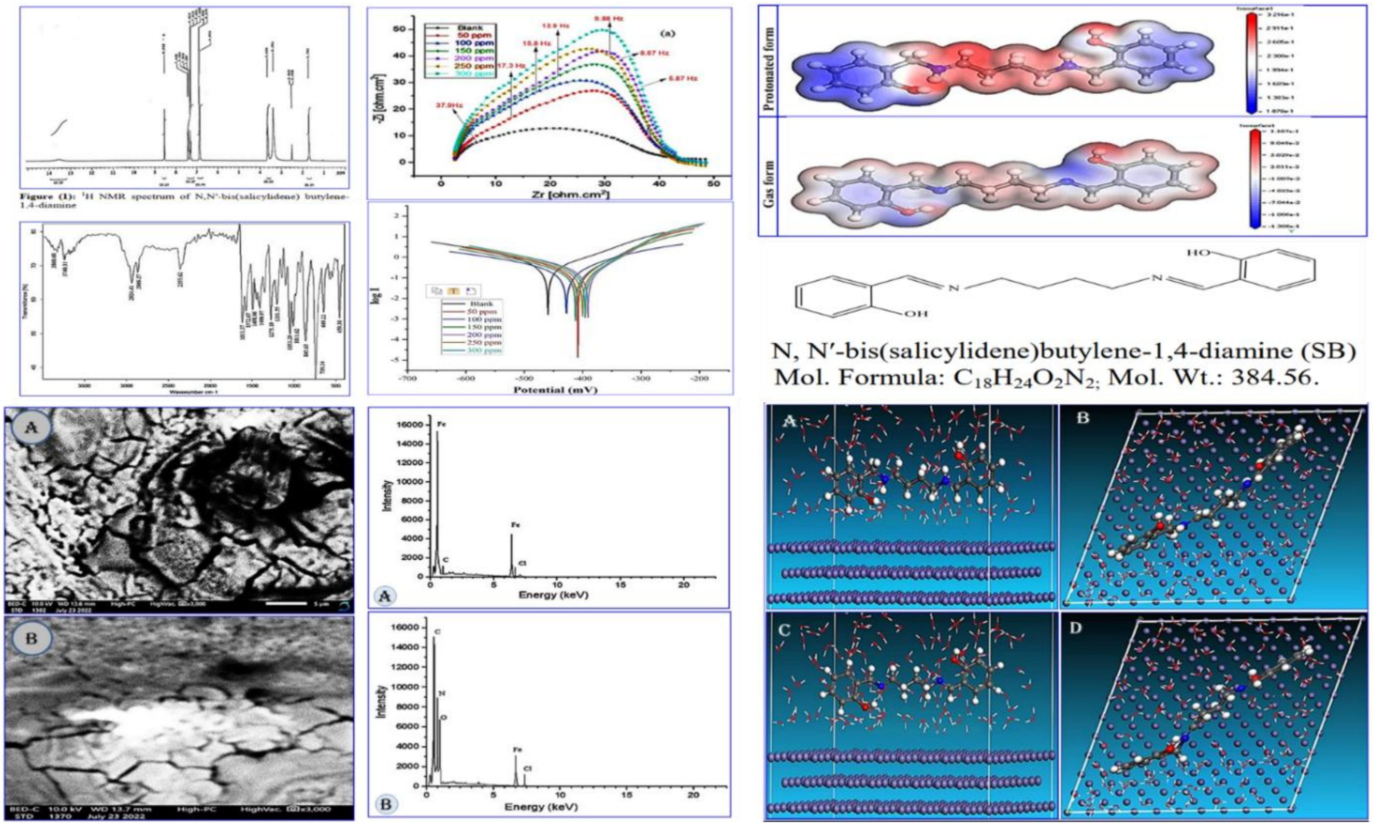


Fig.11: IR, ¹HMNR, *PDP*, *EIS*, *SEM*, *EDS*, MEP, and MCs of SB-inhibitor in HCl solution

6. Conclusion and outlook

From the obtained discussions, *Sb* functions as a *CIs* in various corrosive systems exhibiting high efficacy by adsorbing onto the metallic surface via >C=N– (imine) that facilitating a strong bonding with the metal surface. Appropriately substituted aromatic *Sb*, endowed with polar functional groups, have the ability to form chelating complexes with metal ions. As a result, they are expected to serve as more effective *CIs* compared to their non-substituted counterparts. A review of the literature suggests that *Sb* inhibitors are primarily employed as *CIs* for various *CS* alloys. The majority of *Sb* inhibitors operate as mixed-type *CIs*, effectively hindering both Tafel reactions. From EIS analysis, it is apparent that *Sb* inhibitors function as interface-type *CIs*. Additionally, the literature review highlighted that achieving an appropriate balance between hydrophilicity and hydrophobicity is essential for the effectiveness of *Sb* inhibition. Excessive hydrophobicity may adversely affect the corrosion inhibition capabilities of *Sb* by diminishing its solubility in polar solvents. Moreover, it has been noted that most *Sb* compounds have been assessed as *CIs* in less aggressive environments. Therefore, their application warrants further investigation in industrial processes such as acid descaling, acid pickling, and oil-well acidification, which typically involve highly acidic solutions like 15–28% HCl and H_2SO_4.

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