Schiff Bases as Corrosion Inhibitors: A Comprehensive Review of Synthesis, Mechanisms, and Applications

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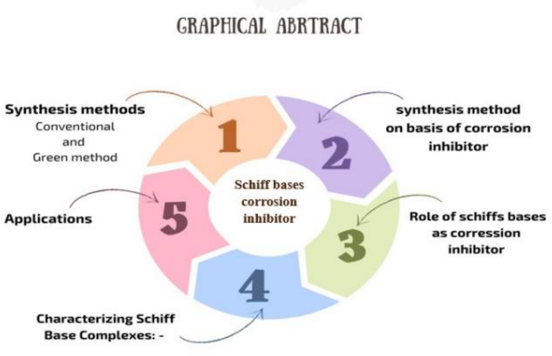
Abstract

The characteristics which are related to the chemistry of Schiff bases, some distinct class of chemical products formed by the condensation process of primary amines and carbonyls compounds together have made them intriguing corrosion inhibitors. This abstract helps to explore different methods used for the synthesis of Schiff bases precisely designed as corrosion inhibitors, their act in allay corrosion and the multiple usage of complexes of Schiff base in corrosion protection. The synthesis of Schiff bases tailored for corrosion inhibition involves the strategic combination of suitable amine and carbonyl precursors. This section discusses various synthesis methods, including condensation reactions and template-assisted approaches, highlighting their impact on the resulting corrosion inhibition properties. Schiff bases exhibit inherent electron-donating and metal-coordinating capabilities, making them effective corrosion inhibitors. This section explores the mechanics behind Schiff bases' corrosion prevention properties, including how they can block aggressive species, modify electrochemical processes, and produce protective layers on metal surfaces. Across the board classification act as an important role in finding the properties and structure of complexes of Schiff bases. This part reviews the analytical method i.e. X-ray crystallography, electrochemical techniques which depicts the corrosion inhibitor complexes and spectroscopy. These complexes have established widespread usage in different industries as corrosion allay. This part specifically shows their usage in inhibiting corrosion for different environments, incorporating aqueous and aggressive industrial settings. Many case studies and practical applications shows and demonstrate the efficiency of these complexes as corrosion inhibitor which makes them easy, sustainable and more cost effective alternative way for corrosion control.



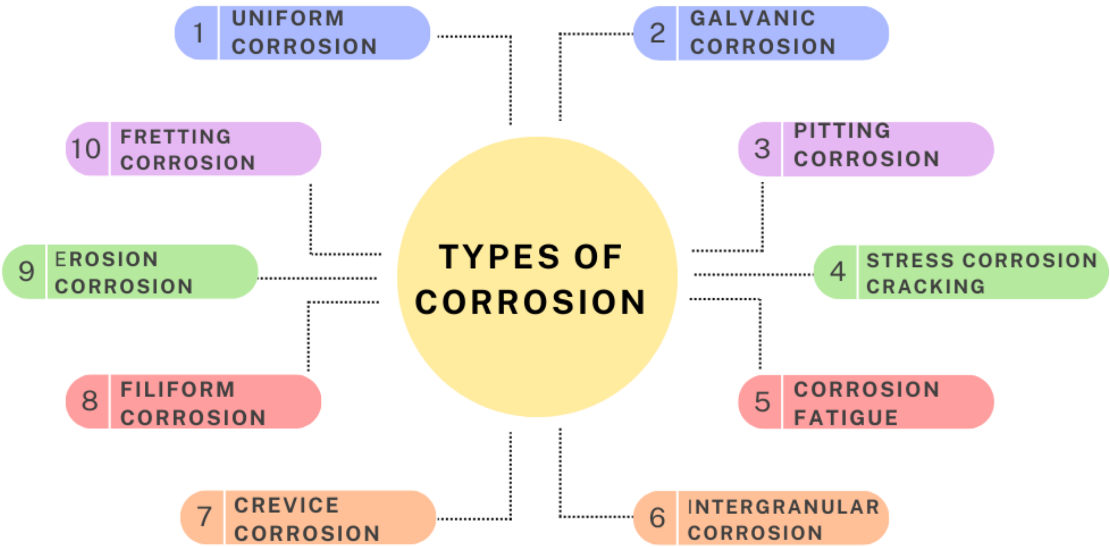
Keywords:-Schiff bases, transition metal complex, corrosion inhibitors, synthesis method

Introduction:-

Corrosion inhibitors are substances used to mitigate or prevent the degradation of metals caused by corrosion, which is the gradual deterioration of materials due to chemical reactions with the environment. These inhibitors function by forming a protective layer on the metal surface, hindering the corrosive processes such as oxidation or reduction reactions. They act as a barrier, preventing the corrosive agents from coming into direct contact with the metal, thereby reducing the rate of corrosion [1]. Corrosion inhibitors find extensive application across various industries, including manufacturing, oil and gas, automotive, and infrastructure, to prolong the lifespan and integrity of metal structures and equipment. Schiff bases, on the other hand, are a class of organic compounds derived from the condensation reaction between primary amines and carbonyl compounds. They possess a distinctive structure with an azomethine (-C=N-) functional group. Schiff bases exhibit diverse chemical properties and have garnered significant attention in various fields, including medicinal chemistry, coordination chemistry, and material science. In the realm of corrosion inhibition, Schiff bases have demonstrated promising characteristics as corrosion inhibitors for metals [2]. Their ability to coordinate with metal surfaces enables the formation of protective layers, inhibiting the electrochemical reactions responsible for corrosion. The presence of nitrogen and other functional groups within Schiff bases facilitates strong interactions with metal surfaces, leading to the formation of stable complexes that shield the metal from corrosive environments. Due to these advantageous properties, Schiff bases have been explored and developed as effective corrosion inhibitors in different industrial applications. Their versatility, tunable structures, and corrosion inhibitive properties make them a promising area of research in the in the field of corrosion science and materials engineering .field of corrosion science and materials engineering. Corrosion inhibitors can be closely related to transition metal complexes due to the ability of these complexes to act as effective corrosion inhibitors for metals [3]. Transition metal complexes possess unique chemical properties owing to their partially filled d orbitals, allowing them to form stable coordination compounds with various ligands. This property makes them suitable candidates for corrosion inhibition purposes. Transition metal complexes can coordinate with the metal surface, forming a protective layer that inhibits the electrochemical reactions responsible for corrosion. The coordination bonds between the transition metal complex and the metal surface create a barrier that prevents corrosive substances from accessing the metal, thereby reducing the corrosion rate [4].

The choice of ligands in these complexes significantly influences their corrosion inhibition properties. Certain ligands can enhance the stability of the complex and promote the formation of a more effective protective layer on the metal surface. Additionally, the ability of transition metal complexes to undergo redox reactions can aid in the formation of passivating layers that protect the metal from further corrosion. The relationship between corrosion inhibitors and transition metal complexes lies in the latter's ability to form stable coordination compounds with metals, leading to the creation of protective layers that mitigate corrosion by inhibiting detrimental electrochemical reactions at the metal surface. The study of corrosion in mild steel gains heightened significance, especially in acidic solutions, reflecting the expanding industrial use of such environments [5]. The action of strong acids on the surfaces of equipment becomes a focal point, demanding a deeper understanding of corrosion mechanisms. This study becomes essential for industries relying on mild steel components, guiding them in developing strategies to mitigate corrosion effects and ensuring the longevity and reliability of their equipment in the face of challenging environmental conditions

1.1 Types of corrosion:-



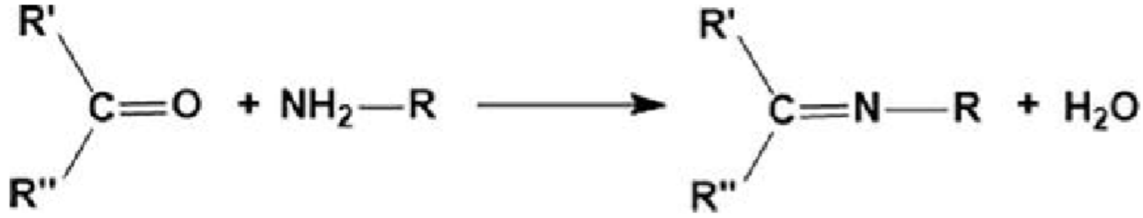
- Uniform Corrosion is the most common and fundamental type, characterized by an even degradation across the entire exposed surface of a metal. This gradual loss of material manifests as a general thinning or dissolution of the metal, occurring uniformly. It is often observed as a surface that displays overall corrosion without localized damage, resulting in a reduction of the metal's thickness over time [6].
- Galvanic Corrosion arises when dissimilar metals come into contact within an electrolytic environment. An electrochemical reaction occurs between these metals, accelerating the corrosion of the more reactive (less noble) metal, while the other metal remains comparatively unaffected. This phenomenon occurs due to the flow of electrons between the dissimilar metals, leading to corrosion at the expense of the less noble metal.
- Pitting Corrosion is a localized form of corrosion resulting in the formation of small pits or craters on the metal surface [7]. Despite its limited area of impact, pitting corrosion can be highly destructive, as it can penetrate deeply into the material, causing structural damage and compromising the integrity of the metal.

- Crevice Corrosion occurs in confined spaces or crevices where there's a difference in the environment compared to the surrounding area. This corrosion arises due to the stagnation of the electrolyte within these confined regions, leading to severe damage in localized areas. The presence of these stagnant environments exacerbates the corrosive process, resulting in accelerated degradation [8].
- Corrosion fatigue is a phenomenon where the combination of cyclic mechanical loading and a corrosive environment leads to accelerated crack growth and failure in a material. It occurs due to the repetitive application of stress combined with the corrosive action, resulting in cracks initiating and propagating faster than they would in a purely mechanical or purely corrosive environment.
- Stress Corrosion Cracking (SCC) arises when a metal is subjected to tensile stress in a corrosive environment. It leads to the initiation and propagation of cracks within the material, often without significant visible surface corrosion. This type of corrosion is particularly hazardous as it can cause sudden material failure due to the development of cracks [9].
- Erosion Corrosion occurs due to the combined effects of both corrosion and mechanical wear caused by high-velocity fluids or particles on the metal surface. The abrasive action of these high-velocity substances exacerbates the corrosive process, leading to accelerated material loss.
- Filiform corrosion, also known as underfilm corrosion, is a type of corrosion that occurs under thin films of protective coatings, typically on metals like aluminum or coated steel. It appears as worm-like filaments or trails beneath the paint or protective coating.
- Intergranular Corrosion targets the grain boundaries of a metal. It occurs due to the precipitation of impurities along these grain boundaries, making these areas more susceptible to corrosion [10]. This type of corrosion can lead to the degradation of the metal along its grain boundaries, compromising its structural integrity.
- Fretting corrosion is a form of wear-related corrosion that arises at the contact interfaces between two surfaces under slight relative motion and in the presence of a corrosive environment.

1.2. Schiff bases: -

Schiff bases are organic compounds that play a crucial role in coordination chemistry. They are characterized by a specific structure, which is typically derived from the condensation reaction between a primary amine and a carbonyl compound [11].

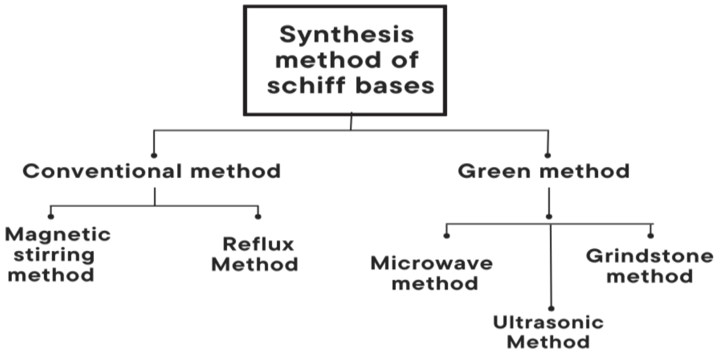
- The general structure of a Schiff base involves the formation of a carbon-nitrogen double bond (C=N) resulting from the reaction between the amino group (-NH2) of a primary amine and the Carbonyl group (C=O) of a carbonyl compound, such as an aldehyde or a ketone [12, 13]. The resulting imines' or azomethine linkage is a key feature of Schiff bases [14].



In this reaction, R and R' represent organic groups attached to the carbon and nitrogen atoms, respectively [15]. The formation of this C=N bond imparts unique chemical properties to Schiff bases, making them versatile ligands in coordination complexes with transition metals. These complexes often exhibit interesting and valuable properties, making Schiff bases important in various fields, including corrosion inhibition, as explored in the context of the review paper [16][17]

1.2.1. Synthesis method of Schiff bases:-

Schiff bases can be synthesized using conventional methods, and two common approaches involve magnetic stirring and reflux [18]



a) **Conventional method**: -

Schiff bases, versatile organic compounds with a carbon-nitrogen double bond, are often synthesized using conventional methods, and two common techniques involve magnetic stirring and reflux [19]. In the magnetic stirring method, equimolar amounts of amines and aldehydes or ketones are combined in a suitable solvent within a reaction vessel [20]. A magnetic stir bar is introduced to facilitate uniform mixing, and the reaction proceeds under the influence of magnetic stirring. This method is particularly suitable for reactions conducted at room temperature or with moderate heating. On the other hand, the reflux method involves mixing the reactants in a round bottom flask with a suitable solvent, connecting it to a reflux condenser to establish a closed system [21]. The reaction mixture is then heated under reflux conditions, allowing the reactants to condense and react at an elevated temperature. Reflux methods are advantageous for reactions that benefit from prolonged heating [22]. In both cases, the progress of the reaction is monitored using techniques such as thin-layer chromatography, and the final product is typically isolated through filtration or extraction [23]. These conventional methods provide foundational approaches to Schiff base synthesis, with the choice between magnetic stirring and reflux depending on factors like reactant properties and desired reaction conditions [24].

b) Green method: -

Schiff bases, known for their diverse applications, can be synthesized through environmentally friendly green methods, presenting a sustainable alternative to conventional approaches [25].

One notable green method involves microwave-assisted synthesis, wherein equimolar amounts of amines and aldehydes or ketones are mixed in a green solvent such as water or ethanol [26]. The reaction mixture is exposed to microwave irradiation, significantly reducing reaction times and enhancing efficiency [27].

- Another green method utilizes grinding or the grinding stone method, where the reactants are manually ground together in the presence of a solvent or grinding aid. This method offers simplicity and eliminates the need for excessive solvent use [28].
- Lastly, the ultrasonic method employs ultrasonic waves to accelerate the reaction between amines and carbonyl compounds. The ultrasonic waves create cavitation, promoting more efficient mixing and enhancing the reaction. These green methods align with sustainable principles by utilizing environmentally friendly solvents, reducing energy consumption, and minimizing waste, offering promising avenues for the synthesis of Schiff bases with reduced environmental impact [29].

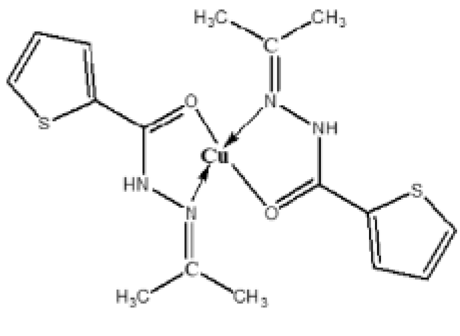
2. Transition metal complexes as schiff bases for corrosion inhibitor :-

Transition metal complexes, particularly those involving Schiff bases, have garnered attention as effective corrosion inhibitors due to their ability to form stable compounds with metals. Schiff bases are derived from the condensation reaction between primary amines and carbonyl compounds and contain an azomethine (-C=N-) functional group [30]. They can coordinate with metal ions on the surface of metals, creating protective layers that inhibit corrosion. Here is an example of a transition metal complex involving a Schiff base:

i. **Consider the synthesis of a copper(II) Schiff base complex as a corrosion inhibitor:**

The Schiff base ligand, derived from the condensation of an aldehyde (such as benzaldehyde) and an amine (such as aniline), forms a chelate complex with copper(II) ions. The general structure involves the coordination of the nitrogen atom from the azomethine group (-C=N-) of the Schiff base to the copper(II) ion, forming a five-membered chelate ring. This coordination results in the formation of a stable complex where the copper ion is surrounded by the ligand's atoms [31].

General Structure:



$[Cu(L)_2]$ (1)

- Cu represents the copper(II) ion.
- L represents the Schiff base ligand coordinated to the copper(II) ion.

This complex can interact with the metal surface, forming a protective layer that impedes the corrosion process by acting as a barrier against corrosive agents.

Absolutely, transition metal complexes, including those involving copper(II) ions and specific ligands like Schiff bases, are versatile and find applications across various fields due to their unique properties and react activities [32].

1. **Catalysts:** Copper complexes can serve as catalysts in a wide range of chemical reactions, including organic synthesis, oxidation-reduction reactions, and more. Their ability to undergo redox reactions and activate substrates makes them valuable in catalyzing various chemical transformations.
2. **Sensors:** Copper complexes can be utilized in sensor technologies due to their sensitivity towards specific analytes or conditions. They can undergo changes in their electronic or spectroscopic properties in the presence of certain molecules or environmental factors, making them useful in sensing applications.
3. **Corrosion Inhibitors:** As previously discussed, copper(II) complexes with suitable ligands, such as Schiff bases, can act as corrosion inhibitors. These complexes form protective layers on metal surfaces, inhibiting the electrochemical processes responsible for corrosion, thus prolonging the lifespan of metal structures and equipment.

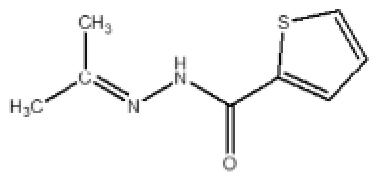
   The design and modification of ligands in these complexes play a crucial role in tailoring their properties for specific applications [33]. For instance, altering the structure of the Schiff base ligand or introducing different functional groups can significantly impact the complex's stability, reactivity, and effectiveness in various applications.

ii. Consider the synthesis of a Schiff base hl complex as a corrosion inhibitor:-

The synthesis of a Schiff base complex (denoted as HL) as a corrosion inhibitor typically involves the formation of a coordination compound between a metal ion and the Schiff base ligand. The Schiff base ligand is usually derived from the condensation reaction between an aldehyde and an amine.

Let's consider the general structure and synthesis process:

The Schiff base ligand (HL) is formed by the condensation reaction between an aldehyde, such as benzaldehyde (PhCHO), and an amine, such as aniline ($PhNH_2$). The resulting ligand contains an azomethine (-C=N-) functional group [34].



HL

Schiff Base Ligand (HL): R-CH=N-R’ Where:

- RR and R’R’ represent the organic groups derived from the aldehyde and amine, respectively.

  Synthesis: The synthesis of the Schiff base complex (HLHL) as a corrosion inhibitor involves the coordination of this ligand to a suitable metal ion, forming a stable complex.
- The synthesis of Schiff base complexes as corrosion inhibitors finds applications across various fields due to their unique properties and reactive activities. Schiff bases, derived from the condensation reaction between primary amines and carbonyl compounds, possess an azomethine (-C=N-) functional group, making them versatile ligands for coordinating with

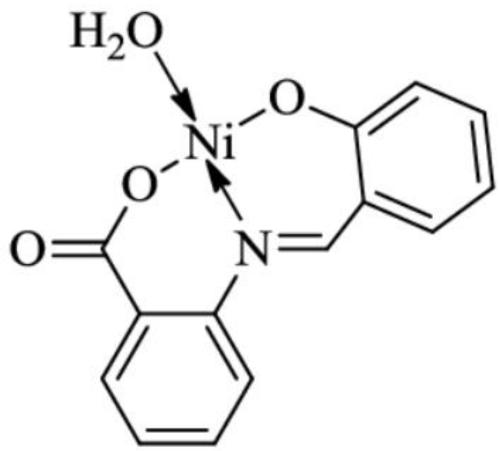
metal ions and applications across various fields due to their unique properties and react activities.

- The versatility of Schiff base complexes lies in their tunable structures and ability to form stable coordination compounds with metal ions. This versatility allows for the customization of these complexes to suit specific corrosion scenarios and various metal substrates.
- Their potential as corrosion inhibitors is attributed to their capability to form protective layers on metal surfaces, hindering the electrochemical reactions responsible for corrosion [35]. Moreover, the ability to tailor their chemical structures enables researchers to optimize their inhibitive properties for different types of metals and corrosive environments.

iii. **Another example of the synthesis of a Schiff base complex for corrosion inhibition involves the formation of a nickel(II) Schiff base complex.**

The Schiff base ligand, derived from the condensation of an aldehyde (e.g., salicylaldehyde) and an amine (e.g., ethylenediamine), forms a coordination complex with nickel(II) ions. The Schiff base ligand coordinates with the nickel(II) ion through the nitrogen atom of the azomethine group (-C=N-), creating a stable chelate complex [36].

General Structure: Ni(L)2



Where:

- Ni represents the nickel(II) ion.
- L represents the Schiff base ligand coordinated to the nickel(II) ion.

This nickel Schiff base complex demonstrates potential as a corrosion inhibitor due to its ability to form a protective layer on metal surfaces. The complex interacts with the metal substrate, inhibiting corrosion by preventing the contact of corrosive agents with the metal surface [37].

Applications: This nickel Schiff base complex can find applications in industries such as:

1. **Metal Coatings:** Utilized as coatings or additives to protect metal surfaces in various industrial settings, including manufacturing, where metal components are exposed to corrosive environments.
2. **Electroplating:** Employed in electroplating processes to create corrosion-resistant layers on metal substrates, enhancing their durability and resistance to degradation.
3. **Water Treatment:** Used in water treatment processes to inhibit corrosion in metal pipes and equipment, thereby maintaining the integrity of water supply systems.

4. **Chemical Processing:** Applied in chemical plants and facilities to protect metal equipment and reactors from corrosion caused by aggressive chemicals.
   The tailored design and synthesis of Schiff base complexes, such as nickel Schiff base complexes, provide opportunities for developing efficient and targeted corrosion inhibitors, contributing to the protection and preservation of metal structures across various industrial applications[38].

4. **Schiff bases based on corrosion inhibitors: -**

Quantum dot (s) synthesis methodology	**Substrate**	**Test solution**	**Optimum Dosage (M)**	**Performance**			**Ref**
				Temperature (K)	**Inhibition efficiency (η%)**	**Adsorption isotherm**	
(E)-2-methyl-N-(thiophen-2-ylmethylidene)aniline	Mild steel	1 M HCl	1×10^{-3}	308	90	Langmuir	[38 a]
3-(5-methoxy-2-hydroxybenzylideneamino)-2-(-5-methoxy-2-hydroxyphenyl)-2,3-dihydroquinazoline-4(1H)-one	Mild steel	1 M HCl	1×10^{-3}	300	92	Langmuir	[38 b]
5-((furan-2-yl)methyleneamino)-2H-1,2,4-triazole-3-thiol (FMT), and 5-((thiophen-2-yl)methyleneamino)-2H-1,2,4-triazole-3-thiol	Mild steel	1 M HCl	5×10^{-3}	298	86	Langmuir	[38 c]
4,4'-bis(3-carboxaldehyde thiophene) diphenyl diimino ether	Mild steel	1 M HCl	5×10^{-3}	298	92	Langmuir	[38 d]
N′-[4-(dimethylamino)benzylidene]-4-hydroxybenzohydrazide	Mild steel	0.5M HCl	1×10^{-3}	303	81.5	Langmuir	[38 e]
1,13-bis-[(2-hydroxynaphtaldehyde)4,7,10-trioxatridecane diimine	copper	1M HCl	$7.5\text{x}10^{-5}$	303	87.36	Langmuir	[38 f]

1,5-bis[2-(2-hydroxybenzylideneamino)phenoxy]-3-oxopentane	Aluminium	0.1 M HCl	1×10^{-4}	298	61.4	Temkin isotherm	[38 g]
N-(2-chlorophenyl)salicyaldimine	steel	5% HCl	5×10^{-3}	293	95	Langmuir	[38 h]
3-((4-hydroxybenzylidene)amino)-2-methylquina- zolin-4(3H)-one	Mild steel	1 M HCl	5×10^{-3}	303	96.0	-	[38 i]
2-((1E)-2-aza-2-pyrimidine-2-ylvinyl)thiophene	Carbon steel	0.1 M HCl	1×10^{-4}	293	83.3	Temkin's adsorption	[38 j]
4-((2,3-dichlorobenzylidene) amino)-3- 25 methyl-1H-1, 2, 4-triazole-5(4H)-thione	Mild Steel	1 M HCl	1×10^{-3}	303 K	97.0	Langmuir	[38 k]
2,2'-((1E,1'E)-(cyclohexane-1,2-diylbis(azanylylidene))bis(methanylylidene))diphenol	Magnesium	0.01 M HCl	5×10^{-3}	298	95.10	Freundlich isotherm	[38 l]
4-((thiophen-2-ylmethylene)amino)benzamide	Mild Steel	1 M HCl	1×10^{-2}	298	98.64	-	[38 m]
(E)-4-((2,3-dichlorobenzylidene)amino)-3-methyl-1H-1,2,4-triazole-5(4H)-thione	Mild Steel	1 M HCl	1×10^{-3}	303	97.3	Langmuir	[38 n]
(Z)-4-(((4-propylphenyl)imino)methyl)phenol	Mild Steel	1 M HCl	8×10^{-3}	303	96	Langmuir	[38 o]
(E)-4-((2-(2,4-dinitrophenyl)hydrazono)methyl)pyridine	Mild Steel	1 M HCl	1×10^{-3}	300	80.0	Langmuir	[38 p]
Benzylidene-pyridine-2-yl-amine	Mild Steel	1 M HCl	1×10^{-2}	298	99.16	Langmuir	[38 q]

5. Schiff Bases' Function as Corrosion Inhibitors:

A. Mechanisms of Inhibition:

The way that Schiff bases interact with metal surfaces—especially mild steel—in corrosive situations accounts for their efficiency as corrosion inhibitors. [42]. Understanding the mechanisms underlying their inhibitory action is essential for optimizing their performance. The following elucidates the key mechanisms through which Schiff bases exert their corrosion inhibition:

Adsorption Mechanism: Schiff bases generate a protective coating that serves as a barrier between the metal and the corrosive medium by adhering to the metal surface by adsorption [43]. Environmental conditions, the chemical makeup of the metal surface, and the Schiff base's chemistry all have an impact on this adsorption process. The adsorbed layer prevents corrosive agents from directly interacting with the metal, thereby impeding the corrosion process [44].

Formation of Complexes: Schiff bases can combine with metal ions on the metal surface to generate coordination complexes. This complex formation alters the electronic configuration of the metal, making it less susceptible to oxidation [45]. The coordination complexes act as sacrificial sites, preferentially undergoing corrosion instead of the underlying metal. This sacrificial protection enhances the overall corrosion resistance of the metal [46].

Blocking Active Sites: - Schiff bases actively participate in blocking the active corrosion sites on the metal surface. By adsorbing onto these sites, the Schiff base molecules displace water molecules and other corrosive agents [47]. This displacement provides a localized defense by preventing the electrochemical processes that lead to metal corrosion.

Film Formation: -A stable and protective coating forms on the metal surface as a result of the adsorbed Schiff bases going through a chemical change [48]. By acting as a physical barrier, this coating stops corrosive species from diffusing toward the metal surface. The film's stability and impermeability contribute significantly to the overall corrosion inhibition [49].

Electronic and Steric Effects: -The electronic and steric properties of Schiff bases play a pivotal role in their inhibitory mechanisms [50]. The direction and strength of Schiff bases' adsorption on the metal surface are determined by the presence of certain functional groups as well as the general molecular geometry. Electronic effects contribute to the alteration of the metal's electronic structure, making it less prone to corrosion [51].

C. **Correlation between Structure and Inhibitory Efficiency**:

To maximize Schiff bases' effectiveness as corrosion inhibitors, especially for mild steel in harsh conditions, it is essential to understand the relationship between their molecular structure and inhibitory efficiency. [52]. The nature of substituents, the presence of specific functional groups, and the overall molecular geometry significantly influence the adsorption and protective capabilities of Schiff bases on metal surfaces. The strength of adsorption onto the metal can be directly influenced by the substituents' ability to donate or withdraw electrons, which can affect the electron density distribution inside the molecular framework. [53]. Furthermore, the presence of aromatic or aliphatic moieties, along with heteroatoms like nitrogen and sulfur, contributes to the formation of stable protective films through coordination with metal ions. The steric hindrance introduced by bulky substituents may affect the orientation and packing of Schiff bases on the metal surface, influencing the accessibility of active sites to corrosive species [54]. Additionally, the length and flexibility of the Schiff base backbone play a role in determining the spatial arrangement of functional groups, affecting the overall coverage and stability of the adsorbed layer. Systematic exploration and understanding of these structural parameters enable researchers to tailor Schiff bases for optimal inhibitory efficiency, providing information on the design concepts that are essential for improving mild steel's resistance to corrosion in a variety of hostile settings [55].

6. Complexes of Transition Metals with Schiff Bases: -

The basis for transition metal complexes' powerful function as corrosion inhibitors is laid by their synthesis and stability with Schiff bases [56]. The impact on corrosion inhibition is profound, with the synergistic effects between the metal ion and organic ligand enhancing the overall efficiency of these complexes

A. **Formation and Stability:**

The production and stability of transition metal complexes with Schiff bases lays the groundwork for their potent role as corrosion inhibitors. [57]. The metal ion coordinates with the Schiff base's electron-donating ligand atoms during the complexation process to produce stable complexes. The stability of these complexes is influenced by factors such as the nature of the metal ion, the donor atoms in the ligand, and the overall geometry of the resulting complex [58]. The chelating ability of Schiff bases enhances the stability of the metal complexes, leading to well-defined structures with significant implications for their applications [59].

B. **Impact on Corrosion Inhibition**:

Exploiting the mutually beneficial interactions between the metal ion and the organic ligand, transition metal complexes containing Schiff bases show great promise as inhibitors of corrosion. When the metal ion and Schiff base are coordinated, the inhibitory efficiency is higher than when the components are separated. [60]. The metal complex, through its interactions with the metal surface, forms a protective layer that impedes corrosive attack. The electron-donating nature of the ligand and the ability of the metal ion to undergo redox reactions contribute to the overall corrosion inhibition mechanism. The coordination complex, acting as a sacrificial site, undergoes corrosion in preference to the underlying metal, thus extending the longevity and durability of the material in corrosive environments [61].

C. Synergistic Effects in Combination with Schiff Bases:

The combination of Schiff bases with transition metal complexes introduces synergistic effects that amplify their corrosion inhibition capabilities. The cooperative action arises from the dual functionality of the ligand and the metal ion, working in tandem to create a robust defense against corrosion [62]. The Schiff base, with its adsorption mechanism and barrier-forming properties, complements the sacrificial protection offered by the metal complex. This synergistic approach not only enhances the overall inhibitory efficiency but also broadens the spectrum of protection, making it effective across diverse corrosive conditions [63]. Understanding the intricate interplay between Schiff bases and transition metal complexes provides insights into the design of advanced corrosion inhibitors with tailored properties for specific applications Transition Metal Complexes with Schiff Bases: -

7. Analytical Techniques for Characterizing Schiff Base Complexes: -

Analyzing Schiff base complexes requires a range of analytical techniques to understand their structures, compositions, and properties. Here are five key analytical techniques used for characterizing Schiff base complexes:

(A). UV-Visible Spectroscopy:

UV-Visible spectroscopy stands as a powerful analytical tool, illuminating the electronic landscape of Schiff base complexes by measuring their absorption of ultraviolet and visible light. Within these complexes, electronic transitions unfold as electrons navigate between energy levels, offering a dynamic window into the compound's intricate electronic structure [64]. As photons of UV or visible light are absorbed, electrons undergo transitions from lower to higher energy states, revealing characteristic absorption bands [65]. The wavelengths at which these bands manifest provide a fingerprint for the molecular architecture, offering insights into the conjugation, delocalization, and coordination of electrons within the Schiff base complex. This technique is particularly adept at elucidating the presence of metal-ligand charge transfer and the nature of ligand-metal interactions. The wealth of information extracted from UV-Visible spectra aids researchers in unraveling the nuanced electronic intricacies of Schiff base complexes, guiding the design and comprehension of these compounds in diverse applications, from catalysis to corrosion inhibition [66].

(B). Infrared (IR) Spectroscopy: Probing Molecular Vibrations in Schiff Base Complexes:

Infrared (IR) spectroscopy is a fundamental analytical technique that plays a pivotal role in unraveling the molecular architecture of Schiff base complexes. Operating on the principle of molecular vibrations, IR spectroscopy detects the absorption of infrared radiation by covalent bonds within a molecule [67]. In the context of Schiff bases, this technique provides invaluable insights into the composition and bonding patterns of the complex.

- As the sample absorbs infrared radiation, vibrational transitions occur, resulting in characteristic peaks on the IR spectrum. These peaks correspond to specific bond vibrations, such as stretching or bending modes of functional groups within the Schiff base ligands [68]. By analyzing the positions and intensities of these peaks, researchers can discern crucial information about the complex's structure, including the presence of key functional groups and the coordination environment around the metal center.
- IR spectroscopy is particularly adept at elucidating the coordination modes of Schiff bases, aiding in the characterization of their metal-ligand interactions [69]. This analytical method serves as an indispensable tool in the hands of chemists and researchers, enabling a deeper understanding of the vibrational fingerprints embedded in Schiff base complexes and informing the design and application of these compounds in fields ranging from coordination chemistry to catalysis.

(C). **Nuclear Magnetic Resonance (NMR) Spectroscopy**:

NMR spectroscopy analyzes the magnetic properties of atomic nuclei in a magnetic field. It provides information about the local environment of nuclei, helping to deduce the structure and connectivity of atoms in a molecule. Imagine molecules as tiny magnets. Nuclear Magnetic Resonance (NMR) spectroscopy is like a detective tool that helps us understand how these molecular magnets behave. When we put a sample in an NMR machine and apply a magnetic field, certain atoms within the molecules respond by absorbing radiofrequency energy [70]. As these atoms absorb and release energy, the NMR machine detects these signals, providing a detailed map of the molecule's structure. It's like listening to a unique musical tune played by each molecule. In the context of Schiff base complexes, NMR spectroscopy helps chemists decipher the arrangement of atoms, revealing how they connect and interact. This method is crucial in understanding the shape and identity of molecules, guiding scientists in their quest to create new materials, drugs, or unravel the mysteries of chemical reactions [71]. So, NMR spectroscopy is like a molecular storyteller, sharing the secrets hidden within the atomic world. NMR is valuable for elucidating the structure of Schiff bases and their metal complexes. It can reveal details about ligand conformations, metal-ligand interactions, and the coordination geometry of the metal center [72].

(D). X-ray Crystallography:

In X-ray crystallography, a crystal is exposed to X-rays, and the diffraction pattern that results is examined [73]. The pattern gives details on how atoms are arranged in three dimensions within a crystal lattice.

- X-ray crystallography is a powerful technique for determining the precise molecular structure of Schiff base complexes. It yields information about bond lengths, bond angles, and overall geometry, offering detailed insights into the arrangement of atoms in the complex [74].

(e). **Thermal Analysis: -**

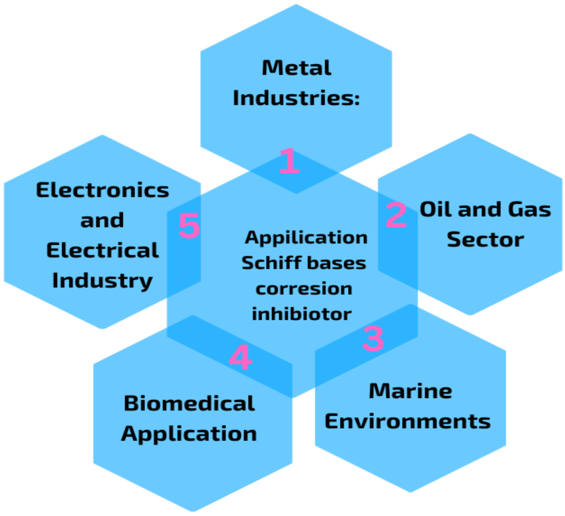
Thermal Analysis, employing techniques like Differential Scanning Calorimetry (DSC) and Thermo gravimetric Analysis (TGA), serves as a thermal detective, unraveling the intricate stability of Schiff base complexes. Picture these analyses as thermal magnifying glasses that help researchers investigate how Schiff base complexes respond to changes in temperature [75].

- Differential Scanning Calorimetry (DSC): DSC is like a sensitive thermometer for molecules. It measures the heat flow into or out of the Schiff base complex as the temperature changes. Peaks and valleys in the DSC curve indicate phase transitions or reactions occurring within the complex [76]. This provides crucial insights into the temperatures at which the complex undergoes transformations, such as melting or crystallization.

8. Advantage and disadvantages of corrosion inhibitor:

Aspect	Advantages	Disadvantages	Reference
Effectiveness	- High inhibitory efficiency, often comparable to conventional inhibitors.	- Effectiveness may vary depending on the specific Schiff base and metal ion used.	[77]
Versatility	- Versatile ligands allow for tailoring of structures to optimize inhibition.	- Synthesis and optimization can be time-consuming.	[78]
Eco-Friendly	- Schiff bases are often derived from readily available, environmentally friendly starting materials.	- Some Schiff base precursors may involve toxic reagents or solvents in the synthesis process.	[79]
Coordination Abilities	- Coordination to metal ions enhances inhibitory properties and stability.	- Formation of stable complexes may require specific conditions and coordination geometries.	.[80]
Film Formation	- Schiff bases can form protective films on metal surfaces, hindering corrosion.	- Film formation may be influenced by environmental conditions and the presence of other chemical species.	.[81]
Cost	- Generally cost-effective compared to some traditional inhibitors.	- Synthesis and purification processes may incur costs, especially for certain Schiff base ligands.	[82]
Inhibition at Low Concentrations	- Effective inhibition at relatively low concentrations.	- Concentration-dependent, and excessive concentrations may lead to precipitation or other undesirable effects.	[83]
Synergistic Effects	- Synergies with other inhibitors or additives may enhance overall corrosion protection.	- Optimal synergistic combinations may need extensive testing.	[84]
Long-Term Stability	- Some Schiff bases demonstrate long-term stability and sustained inhibitory effects.	- Stability may be influenced by environmental factors, and prolonged exposure studies are essential for validation.	[85]
Biocompatibility (for certain apps)	- Some Schiff bases and their complexes exhibit biocompatibility, suitable for biomedical applications.	- Biocompatibility is ligand-specific, and not all Schiff bases are suitable for applications in biological or medical fields.	[86]
Customization	- Structural diversity allows for tailoring properties for specific applications.	- Complex synthesis and characterization processes may limit the ease of customization.	.[87]

9. Various Application of corrosion inhibitor:



7.1 Metal Industries: Mild Steel Protection with Schiff Bases

In the metal industry, Schiff bases play a vital role in protecting mild steel components from corrosion [88]. Mild steel is a commonly used alloy in various applications, and its protection is crucial for maintaining structural integrity and preventing material degradation [89]. Here's how Schiff bases contribute to mild steel protection in metal industries

Corrosion Protection in Pipelines, Storage Tanks, and Structural Elements Pipelines:

- Pipelines used in the metal industry, especially for transporting liquids or gases, are susceptible to corrosion due to exposure to corrosive substances and environmental conditions [90].
- Schiff bases are employed as corrosion inhibitors in pipeline coatings. These inhibitors form a protective layer on the inner surface of the pipeline, preventing the corrosive medium from directly interacting with the mild steel [91]. This helps in reducing corrosion rates and extending the lifespan of the pipelines.

Storage Tanks:

- Storage tanks, which hold various liquids or chemicals, are prone to corrosion, especially at the liquid-metal interface [92].
- Schiff base coatings are applied to the interior surfaces of storage tanks. These coatings act as a barrier, inhibiting the corrosive reactions between the stored substances and the mild steel tank walls [93]. The result is enhanced durability and longevity of the storage infrastructure

Structural Elements:

- Structural elements such as beams, columns, and supports in metal structures are exposed to environmental conditions that can lead to corrosion over time. Schiff bases are incorporated into protective paints or coatings applied to structural components [94]. These coatings form a robust and durable layer that shields the mild steel from environmental factors, preventing corrosion and maintaining the structural integrity of the metal elements. Advantages

7.2. Oil and Gas Sector:

- Pipeline Protection with Schiff Bases In the oil and gas sector, the protection of pipelines from corrosion is a critical consideration due to the harsh and corrosive environments to which these pipelines are exposed. Schiff bases play a
- Crucial role in safeguarding pipelines, contributing to the longevity and reliability of the infrastructure [95].

Corrosion Protection in Oil and Gas Pipelines

1. **Corrosive Environments**:
   Pipelines in the oil and gas sector are exposed to corrosive elements such as hydrogen sulfide (H2S), carbon dioxide (CO2), and moisture. These corrosive environments can lead to the degradation of pipeline materials [96].
2. **Inhibitory Properties of Schiff Bases:**
   Schiff bases are employed as corrosion inhibitors in the protective coatings applied to the external surfaces of pipelines. The inhibitory properties of Schiff bases come into play when they form a protective layer on the pipeline's surface, mitigating the corrosive effects of the surrounding environment.
3. **Extended Lifespan:**

- The use of Schiff base inhibitors helps extend the lifespan of oil and gas pipelines. By reducing the corrosion rates, these inhibitors contribute to the prevention of material degradation, minimizing the need for frequent replacements and maintenance [97].

4. **Reduced Maintenance Costs:**
   The extended lifespan of pipelines resulting from Schiff base protection leads to reduced maintenance costs for the oil and gas companies. This is economically beneficial, as the need for repairs and replacements is significantly diminished.
5. **Enhanced Operational Reliability**: Schiff base inhibitors enhance the operational reliability of oil and gas pipelines. Reliable infrastructure is crucial for the smooth and safe transportation of oil and gas, and the use of corrosion inhibitors helps maintain the integrity of the pipeline system [98].

Advantages of Using Schiff Bases for Pipeline Protection:

- **High Inhibitory Efficiency:** Schiff bases demonstrate high inhibitory efficiency, effectively reducing corrosion rates and protecting pipeline materials.
- **Compatibility with Coatings:** Schiff bases can be incorporated into various types of coatings, such as epoxy or polyurethane coatings, enhancing their compatibility with existing corrosion protection methods.
- **Customization:** Schiff bases offer versatility in formulation, allowing for customization based on the specific corrosive agents present in the oil and gas environment.
- **Environmental Adaptability:** Schiff bases can adapt to different environmental conditions, making them suitable for the varied and challenging climates encountered in the oil and gas sector [99].

7.3. Marine Environments: Schiff Base Applications in Corrosion Protection

Marine environments pose unique challenges for materials due to the corrosive nature of seawater. Schiff bases, known for their versatility and inhibitory properties, find valuable applications in protecting various metal components used in marine structures. One prominent example is the protection of mild steel components in ships, offshore platforms, and underwater structures [100].

Corrosion Protection in Marine Structures

I. **Ship Hulls**: Ship hulls are constantly exposed to seawater, making them susceptible to corrosion. This corrosion can compromise the structural integrity and performance of the vessel.

- Schiff bases are incorporated into antifouling coatings applied to ship hulls. These coatings serve a dual purpose: inhibiting corrosion and preventing the attachment of marine organisms, such as barnacles and algae, which can accelerate corrosion.

II. **Offshore Platforms:** Offshore platforms, including oil rigs and drilling structures, are exposed to aggressive marine conditions, including salt spray and constant moisture [101]. Schiff bases are used as corrosion inhibitors in coatings applied to the structural components of offshore platforms. These coatings provide a protective barrier, preventing corrosion and ensuring the reliability of the platform in harsh marine environments.

III. **Underwater Structures:** Structures submerged in seawater, such as piers, bridges, and underwater pipelines, face accelerated corrosion due to the continuous exposure to saltwater. Schiff bases are employed in coatings for underwater structures. These coatings form a protective layer that hinders the corrosive impact of seawater, preserving the structural integrity of the submerged components.

Advantages of Using Schiff Bases in Marine Environments:

- **Seawater Compatibility**: Schiff bases exhibit compatibility with seawater, making them well-suited for applications in marine environments.
- **Corrosion Inhibition**: The inhibitory properties of Schiff bases effectively reduce corrosion rates, extending the lifespan of metal components in marine structures.
- **Antifouling Effects**: Schiff bases used in antifouling coatings contribute to the prevention of marine organism attachment, reducing the risk of localized corrosion and biofoulingrelated damage.
- **Film Formation:** Schiff bases can form durable protective films on metal surfaces, acting as a barrier against corrosive agents present in seawater.
- **Customization:** The versatility of Schiff bases allows for customization based on the specific requirements of different marine applications, considering variations in salinity, temperature, and exposure conditions

7.4 Biomedical Applications: Schiff Bases in Corrosion Protection for Biocompatible Materials

Schiff bases and their transition metal complexes have garnered attention for their potential biomedical applications, particularly in providing corrosion protection for biocompatible materials. The use of Schiff bases in this context extends beyond traditional corrosion inhibition, as they also contribute to ensuring the safety and longevity of materials intended for biomedical use [102].

Corrosion Protection for Implant Materials

Implant Materials:

- Materials used in biomedical implants, such as orthopedic implants and cardiovascular stents, must exhibit high corrosion resistance to ensure long-term biocompatibility within the human body.
- Schiff bases, known for their versatility and biocompatibility, are incorporated into coatings for implant materials. These coatings act as a protective layer, preventing corrosion and ensuring the structural integrity of the implant over an extended period [103].

Advantages of Using Schiff Bases in Biomedical Applications:

- **Biocompatibility:** Schiff bases and their complexes exhibit biocompatibility, making them suitable for use in contact with biological tissues and fluids.
- **Corrosion Inhibition:** Schiff bases provide effective corrosion inhibition, ensuring that implant materials remain resistant to corrosion in the physiological environment of the human body [104].
- **Tailored Properties:** The structural diversity of Schiff bases allows for the tailoring of their properties, optimizing them for specific biomedical applications and the unique conditions within the human body.
- **Film Formation:** Schiff bases can form protective films on the surfaces of implant materials, preventing direct contact with bodily fluids and minimizing the risk of corrosion [105].
- **Reduced Biotoxicity**: The use of Schiff bases can contribute to reducing the biotoxicity associated with certain metals used in implants, enhancing the overall safety of biomedical devices.

Example Application: Orthopedic Implants

- For instance, in the context of orthopedic implants like joint replacements, Schiff base coatings can be applied to the surface of implant materials, such as titanium or its alloys. These coatings not only protect the implant from corrosion but also contribute to a reduced inflammatory response and improved tissue integration, enhancing the overall success and longevity of the implant [106].

7.5. Electronics and Electrical Industry: Schiff Bases in Corrosion Protection

In the electronics and electrical industry, where the performance and reliability of components are paramount, Schiff bases find application in corrosion protection for mild steel components. The use of Schiff bases contributes to maintaining the integrity and longevity of critical components in electronic and electrical devices [107].

Corrosion Protection in Circuit Components

Circuit Components:

Mild steel components used in electronic and electrical circuits are susceptible to corrosion, which can compromise the functionality and reliability of the devices [108].

Schiff bases are incorporated into protective coatings applied to circuit components. These coatings act as a barrier, inhibiting the corrosive reactions that could degrade the mild steel, ensuring the prolonged reliability of the electronic and electrical devices [109].

Example Application: Printed Circuit Boards (PCBs)

For example, Schiff bases can be integrated into the protective coatings applied to printed circuit boards (PCBs). PCBs are fundamental components in electronic devices, and their reliable performance is essential [110].

- The application of Schiff bases helps prevent corrosion on the exposed metal traces of the PCB, ensuring the continued functionality of the electronic device.
- The use of Schiff bases in the electronics and electrical industry focuses on protecting mild steel components, particularly those used in circuitry. This application ensures the corrosion resistance of critical components, contributing to the overall reliability and functionality of electronic and electrical devices [111].

8. Future direction: -

The future prospects for Schiff bases as corrosion inhibitors for mild steel and transition metal complexes hold promising avenues for research, development, and practical applications. Here are some potential future aspects in this field:

I. **Nanostructure Schiff Bases**: The integration of nanostructure Schiff bases could be a focus for future research. Nano-sized Schiff base particles may enhance the efficiency of corrosion inhibition, providing a higher surface area for interaction with metal surfaces and potentially improving the overall performance of inhibitors.

II. **Smart Coatings and Responsive Materials:** The development of smart coatings incorporating Schiff bases could be explored. These coatings might respond to specific environmental conditions, triggering enhanced corrosion protection when exposed to corrosive agents. This adaptive and responsive nature could lead to more efficient and tailored corrosion inhibition.

III. **Computational Approaches:** Utilizing computational approaches, such as molecular dynamics simulations and quantum chemical calculations, researchers can gain deeper insights into the interactions between Schiff bases and metal surfaces. This could guide the design of novel Schiff base derivatives with optimized inhibitory properties.

IV. **Biodegradable Schiff Bases**: Considering the increasing emphasis on sustainable practices, the development of biodegradable Schiff bases as corrosion inhibitors could be a prospective avenue. Biodegradable inhibitors would address environmental concerns and align with the global shift towards greener and eco-friendly corrosion protection solutions.

V. **Synergistic Inhibitor Systems:** Investigating synergistic inhibitor systems involving Schiff bases could enhance overall corrosion protection. Combining Schiff bases with other corrosion inhibitors, such as organic or inorganic compounds, may result in synergistic effects, providing a comprehensive and improved protection strategy.

VI. **Application in Specific Industries:** Tailoring Schiff bases for specific industries, such as aerospace or automotive, could be explored. Understanding the unique corrosion challenges in different sectors and designing Schiff bases that meet those specific requirements may lead to more targeted and efficient corrosion protection solutions. Long-Term Durability Studies: Conducting long-term durability studies to assess the performance of Schiff bases over extended periods is crucial. This would provide valuable data on the sustained inhibitory effects of Schiff bases, aiding in their practical implementation and ensuring long-lasting corrosion protection.

VII. **In situ Monitoring and Sensor Development**: Integrating Schiff bases into corrosion sensors and developing in situ monitoring techniques could be a futuristic approach. Realtime monitoring of corrosion inhibition effectiveness would enable timely interventions and maintenance, reducing the economic and safety implications of corrosion-related failures.

VIII. **Collaborative Interdisciplinary Research:** Encouraging collaborative efforts between chemists, material scientists, engineers, and industry experts could lead to more holistic solutions. Interdisciplinary research can bridge the gap between fundamental understanding and practical applications, accelerating the development of effective Schiff base-based corrosion inhibitors.

Conclusion: -

The exploration of Schiff bases as corrosion inhibitors for both mild steel and transition metal complexes reveals a versatile and promising avenue in corrosion protection. The diverse applications across various industries underscore the adaptability and efficacy of Schiff bases in safeguarding critical components against corrosive environments. The fundamental understanding of the molecular structure, synthesis methods, and reactivity of Schiff bases provides a solid foundation for their utilization as corrosion inhibitors. Their unique ability to form stable complexes with transition metals adds an extra layer of complexity and functionality to their inhibitory properties. The significance of Schiff bases in corrosion inhibition is highlighted by their widespread use in industries such as metal manufacturing, oil and gas, marine environments, biomedical applications, and the electronics and electrical sector. These applications showcase the versatility of Schiff bases in addressing corrosion challenges in diverse settings, ranging from the harsh conditions of offshore platforms to the intricate demands of biomedical implants. Moreover, the correlation between the structure of Schiff bases and their inhibitory efficiency provides valuable insights for tailoring these compounds to specific industry requirements. As evidenced by the numerous synthetic methods, including both conventional and green approaches, the adaptability of Schiff bases aligns with the growing emphasis on sustainable and environmentally friendly practices in corrosion inhibition. The examination of transition metal complexes with Schiff bases further expands the scope of their applications. The ability of Schiff bases to coordinate with various metal ions enhances their corrosion inhibitory effects, presenting opportunities for innovative solutions in metal protection., Schiff bases emerge as versatile and effective corrosion inhibitors, offering a holistic approach to combatting the destructive effects of corrosion on mild steel and transition metal complexes. Their unique properties, coupled with advancements in synthetic methods and a deepening understanding of their applications, position Schiff as a promising candidate for continued exploration in the realm of corrosion protection.

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