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Review Article

Recent Advances in Azo-Based Corrosion Inhibitors for Steel in Acidic Media: Adsorption Mechanism, Electrochemical Performance, and Theoretical Insights(review article)

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Abstract

Azo and azo–Schiff base derivatives have been widely explored as corrosion inhibitors for steel in acidic environments due to their electron-rich heteroatoms and conjugated π-systems. This review critically examines recent experimental and computational studies, with emphasis on adsorption thermodynamics, electrochemical response, and structure–efficiency relationships in 1 M HCl and H□SO□ solutions. Reported inhibition efficiencies frequently exceed 90%, although performance varies depending on molecular substitution pattern and medium conditions. Adsorption behavior is commonly described by the Langmuir isotherm, with ΔG°ads values (−28 to −42 kJ mol□¹) indicating spontaneous adsorption involving both physical and chemical interactions. Electrochemical impedance spectroscopy and polarization measurements consistently show increased charge transfer resistance and reduced corrosion current density in the presence of azo-based inhibitors. Complementary density functional theory (DFT) calculations further clarify the role of molecular electronic descriptors, such as EHOMO and energy gap

(ΔE), in determining adsorption strength and inhibition performance. By integrating thermodynamic analysis with quantum chemical insights, this review outlines key structure–performance trends and highlights strategic considerations for the rational development of high-efficiency azo-derived corrosion inhibitors

Keywords: Azo-based organic inhibitors, Corrosion inhibition efficiency, Adsorption mechanisms, Electrochemical characterization, Acidic media, Surface analysis, Molecular modeling

1. Introduction

Steel structures exposed to acidic media are highly susceptible to rapid degradation, especially during industrial operations such as pickling, descaling, acid cleaning, and oil-well stimulation [1,2]. In strongly acidic solutions, particularly HCl and H□SO□, the metal surface undergoes accelerated dissolution, resulting in material weakening and considerable economic impact [3]. To minimize such damage, the application of organic corrosion inhibitors has become one of the most widely adopted and cost-effective protection strategies [4,5].

Organic inhibitors that contain heteroatoms such as N, O, and S are generally more effective because these atoms provide active adsorption sites on the metal surface [5,7]. Their conjugated π-electron systems further promote surface interaction, leading to the formation of a protective barrier that slows down corrosion [3,8]. Within this group, azo-based compounds (–N=N–) and their corresponding Schiff base derivatives have attracted particular interest due to their flexible molecular structures and high electron density [9–12]. The combination of azo linkages with imine groups (–C=N–), aromatic rings, and additional substituents enhances adsorption strength and facilitates interaction with vacant d-orbitals of iron atoms [15–19].

However, the reports on azo-based corrosion inhibitors are all experimental work and lack comparisons with adsorption thermodynamics, electrochemical reactions, and theoretical predictions [3, 8]. Much of the research has been focused on each of these separately, making it difficult to build a consistent structure-activity relationship [7, 9]. Specifically, the connection between molecular structure, free adsorption enthalpy (ΔG°ads), and DFT-calculated electronic descriptors has not been comprehensively studied across multiple acidic media [10, 15–18]. Azo-based corrosion inhibitors are promising candidates for steel in acid media, and this review systematically reviews the progress of azo-type corrosion inhibitors in comparison with other materials [3, 8]. These include the adsorption behavior, thermodynamic

parameters, electrochemical characterization, and computational analysis [10, 15–18]. The unifying nature of this approach harnesses the various dimensions described herein to explain the SAR as well as where gaps in knowledge exist for further exploration [7, 19]. Despite several review articles covering azo-based corrosion inhibitors, the vast majority have failed to address experimental observations, adsorption behavior or computational studies in a single literature perspective. This review takes a more holistic view by connecting adsorption thermodynamics, electrochemical parameters and electronic descriptors in an all-encompassing structure-activity relationship approach. We particularly emphasize the interpretation of ΔG°ads values, charge transfer resistance trends as well as features obtained from DFT calculations in comparison under different acidic conditions. By discussing the similarities and differences between those different works, as well as their methodological limitations if any, here we provide a rational for what determines the corrosion inhibition efficiency in this class of compounds that will help to support future rational design approaches on azo-based corrosion inhibitors.

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2. Fundamental Aspects of Corrosion in Acidic Media

Steel corrosion in acidic environments is primarily governed by electrochemical reactions occurring at the metal–solution interface [38,39]. In mineral acids such as hydrochloric acid (HCl) and sulfuric acid (H□SO□), the anodic dissolution of iron proceeds according to:

$$Fe \rightarrow Fe^{2+} + 2e^{-}$$

Simultaneously, the cathodic reaction typically involves hydrogen evolution:

$$2H^{+} + 2e^{-} \rightarrow H_2$$

The presence of aggressive anions, particularly chloride ions, accelerates metal dissolution by destabilizing passive films and promoting localized attack [38]. As a result, corrosion rates significantly increase in industrial processes such as pickling and acid cleaning [39].

The application of organic corrosion inhibitors represents one of the most practical mitigation strategies. These compounds adsorb onto the metal surface, forming a protective barrier that reduces active corrosion sites.

3. Azo-Based Corrosion Inhibitors: Structural Features

Azo-based compounds are characterized by the presence of the azo linkage (–N=N–), which plays a crucial role in their adsorption behavior and corrosion

inhibition efficiency. [15,18,20]. The azo group contributes to electron delocalization and enhances π-conjugation within the molecular framework, facilitating interaction with the metal surface [17,21,28].

In addition to the azo linkage, many effective inhibitors incorporate auxiliary functional groups such as imine (–C=N–), hydroxyl (–OH), amine (–NH□), and other heteroatom-containing substituents.[15,17,21] These functional groups serve as active adsorption centers capable of donating lone pair electrons to vacant d-orbitals of the metal surface, strengthening chemisorption interactions.[18,30]

The presence of aromatic rings further enhances adsorption through π–d orbital interactions, enabling planar molecules to achieve improved surface coverage.[20,22] Compounds with extended conjugation systems often demonstrate higher inhibition efficiencies because of increased electron density and stronger metal–inhibitor interactions [21,29].

Moreover, structural modifications such as the incorporation of electron-donating substituents or the design of bis-azo and azo–Schiff base hybrids may significantly improve inhibition performance [19,27]. These structural features can increase the number of adsorption sites and promote the formation of a compact protective film, thereby reducing the number of active corrosion sites on the steel surface.[19,21,29]

3.1.Influence of Functional Groups on Inhibition Efficiency

The inhibition efficiency of azo-based compounds is strongly influenced by the nature, number, and position of functional groups within the molecular structure [15,17]. The presence of electron-donating substituents such as hydroxyl (–OH), amino (–NH_2), and methoxy (–OCH□) groups enhances electron density over the aromatic system, thereby improving adsorption capability on the steel surface [29]. Increased electron density facilitates stronger donor–acceptor interactions between inhibitor molecules and vacant d-orbitals of iron atoms [18,30].

Imine groups (–C=N–), commonly present in azo–Schiff base derivatives, further contribute to adsorption through lone pair electron donation and possible coordination bonding [15,16]. As a result, azo–Schiff base hybrids often exhibit higher inhibition efficiencies than simpler mono-azo derivatives under comparable acidic conditions[16,19].

Molecular planarity also plays an important role in adsorption behavior. Planar π-conjugated systems can allow better surface coverage and stronger π–d orbital

interactions with the metal substrate. In contrast, sterically hindered substituents may reduce adsorption efficiency by limiting surface packing [20,22,29].

Furthermore, bis-azo derivatives and hybrid systems containing additional heterocycles (e.g., coumarin, pyrazole, thiadiazole) frequently demonstrate enhanced inhibition performance due to multiple adsorption centers and extended conjugation. These structural features favor the formation of a dense and stable protective layer that can suppresses both anodic and cathodic corrosion reactions [27,29].

4. Adsorption Behavior and Thermodynamic Parameters.

4.1.Adsorption isotherm.

The adsorption of azo-based inhibitors on steel surfaces is commonly interpreted using classical adsorption isotherm models, among which the Langmuir isotherm is the most frequently applied in corrosion inhibition studies[15,18,22].in many reviewed studies, azo derivatives showed an approximately linear relationship consistent with the Langmuir model, which is commonly interpreted as a first approximation of monolayer adsorption in the absence of strong lateral interactions between adsorbed species[22,40].

Nevertheless, deviations from ideal Langmuir behavior have also been reported and are commonly attributed to surface heterogeneity, intermolecular interactions, competitive ion adsorption, or other non-ideal interfacial effects, which may make alternative models such as Temkin or Freundlich more appropriate in some systems [16,40]. However, the frequent application of the Langmuir model in the reviewed studies suggests that monolayer-type adsorption is commonly used as a practical. approximation; nevertheless, the actual adsorption behavior may still be affected by surface heterogeneity, lateral interactions, and competitive adsorption in acidic media [16,21,40].

4.2.Gibbs Free Energy of Adsorption (ΔG°ads)

The calculated values of standard Gibbs free energy of adsorption (ΔG°ads) reported in the reviewed studies generally range between approximately −28 and −42 kJ mol□¹ [15,18,21,30]. The negative ΔG°ads values generally indicate spontaneous adsorption of inhibitor molecules onto the steel surface[21,30].

Conventionally, ΔG°ads values around −20 kJ mol□¹ are associated with electrostatic interactions (physisorption), while values approaching or exceeding −40 kJ mol□¹ suggest chemisorption involving charge sharing or coordinate bond

formation [41]. The intermediate range observed for many azo derivatives indicates a mixed adsorption mechanism combining physical and chemical interactions [22,27].

This mixed behavior is attributed to the coexistence of π-electron systems and lone pair electrons from heteroatoms (N and O), facilitating strong surface anchoring and stable protective film formation[18,21]. The proposed mixed adsorption mechanism is schematically illustrated in **Figure 1**.

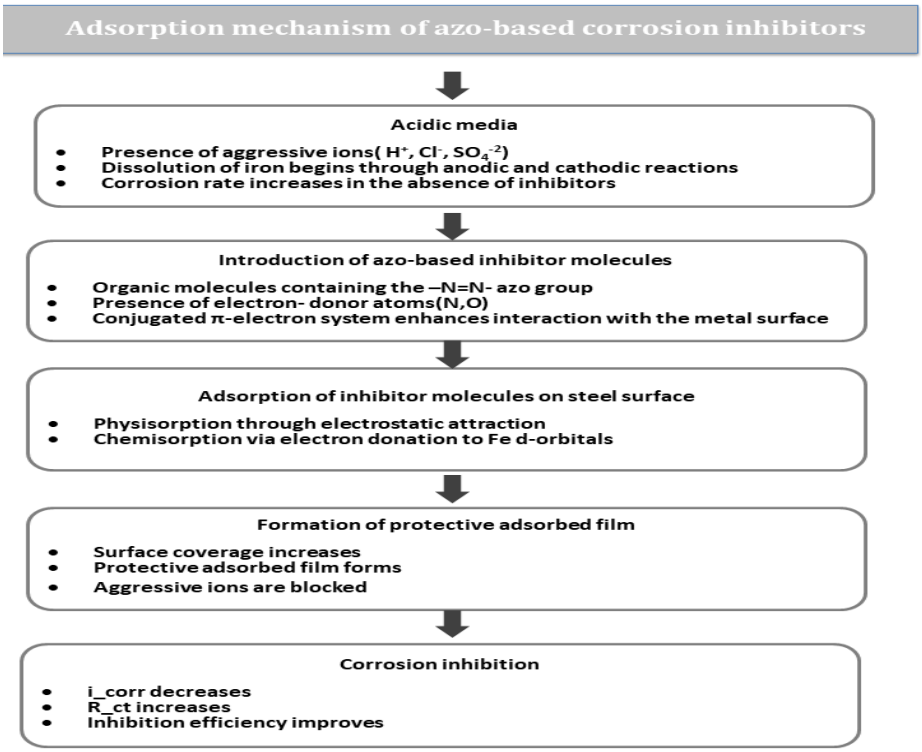

Figure 1: Proposed adsorption mechanism of azo-based corrosion inhibitors on steel surface in acidic medium, illustrating the role of aggressive ions, inhibitor adsorption, protective film formation, and the resulting corrosion suppression through physicsorption and chemisorption.

5. 5.Electrochemical evaluation

5.1.Potentiodynamic Polarization (PDP)

Potentiodynamic polarization (PDP) measurements are widely employed to evaluate the corrosion inhibition performance of azo-based compounds. The addition of inhibitors generally leads to a significant reduction in corrosion current density (i_{corr}), indicating suppression of the overall corrosion rate.

In most reviewed studies, azo derivatives act as mixed-type inhibitors, affecting both anodic metal dissolution and cathodic hydrogen evolution reactions. [15,16,18,19,20,31].

However, slight shifts in corrosion potential (E_{corr}) are often observed, depending on molecular structure and adsorption strength.

The decrease in i_{corr} values in the presence of azo-based inhibitors is primarily attributed to surface adsorption and formation of a protective film that blocks active corrosion sites [20,21].

5.2.Electrochemical Impedance Spectroscopy (EIS)

Electrochemical impedance spectroscopy (EIS) can also shed light on the inhibition mechanism by studying interfacial charge transfer processes. When azo-based inhibitors are introduced, not only is a significant increase in charge transfer resistance (Rct) observed, but also a decrease in double layer capacitance (Cdl). upon inhibitor addition [15,18,20,32].

Therefore, the rise of Rct reflects the increase of electron flow resistance between metal surface and corrosive medium, while the decline in Cdl demonstrates the decreasing local dielectric constant as well as thickness of protective adsorption film [19, 31].

Electrochemical results thus provide powerful support for the inhibition mechanism based on adsorption while showing a strong correlation with thermodynamic parameters obtained from isotherm analysis.

6. Computational and Theoretical Insights

Computational approaches, particularly density functional theory (DFT), have been widely employed to interpret the inhibition performance of azo-based compounds and to rationalize structure–performance relationships [15,21,27,42,43]. DFT calculations provide valuable information about the electronic structure of inhibitor molecules and their affinity toward adsorption on steel surfaces.

Among the most frequently reported electronic descriptors are the highest occupied molecular orbital energy (E_{HOMO}), the lowest unoccupied molecular orbital energy (E_{LUMO}), and the energy gap (ΔE). Higher E_{HOMO} values indicate a stronger tendency of inhibitor molecules to donate electrons to vacant d-orbitals of iron atoms, which enhances adsorption strength and film stability [21,27,42]. Conversely, lower ΔE values suggest higher molecular reactivity, facilitating stronger interaction with the metal surface and improved inhibition efficiency [18,30,43].

Several studies demonstrated correlations between calculated electronic parameters and experimental inhibition efficiencies, supporting the role of molecular planarity, π-conjugation, and heteroatoms in governing adsorption behavior

[15,22,31]. In addition to DFT, molecular dynamics (MD) simulations have increasingly been used to model adsorption configurations, binding energies, and inhibitor orientation at the metal–solution interface, providing a more realistic representation of interfacial interactions under solvent effects [9,19,44]. Overall, these computational techniques complement electrochemical findings and strengthen mechanistic interpretation of azo-based corrosion inhibition [42–44]. The structure–electronic descriptor–performance relationship is schematically summarized in **Figure 2**.

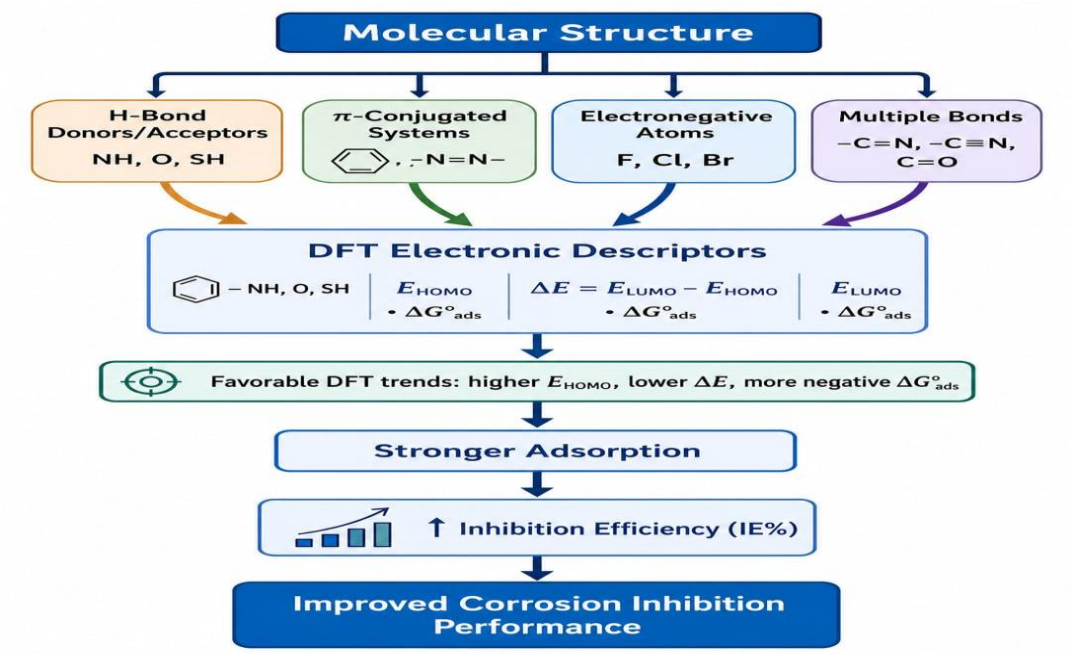

Figure 2: Conceptual correlation between molecular structure of azo-based inhibitors, DFT electronic descriptors (E_{HOMO}, ΔE, ΔG°ads), adsorption strength, and resulting corrosion inhibition efficiency.

A comparative summary of the reviewed azo-based corrosion inhibitors, including structural features, electrochemical performance, thermodynamic parameters, and computational findings, is presented in **Table 1**.

Table 1: Comparative performance of recent azo-based corrosion inhibitors in acidic environments (2020–2026)

Ref.	Key functional group	Metal	Medium	Max IE(%)	Techniques	ΔG° ads (KJ mol-1)	Computational Study
10	(-C=N-) (-N=-) (-OH)	CS	1 M H□SO□	96	WL, SEM,PDP,EIS	-38	DFT
11	(-N=N-) Phenolic (-OH)	MS	1 M HCl	94	EIS,WL	-32	-
12	Azo dye multi (-oH)	CS	1 M HCl	91	PDP	-	-
13	Aromatic azo compound	MS	1 M HCl	-	EIS,WL	-	-
14	(-C=N-)(-N=N-)	MS	1 M HCl	95	WL,EIS,PDP	-37	DFT
15	Diazenyl (-N=N-) π-electron	MS	1 M HCl	97	EIS,WL	-40	DFT
16	Coumarin- azo hybrid	MS	1 M HCl	98	WL,EIS	-41	DFT
17	Coumarin–azo Schiff	MS	1 M HCl	-	EIS,PDP,SEM	-	DFT
18	Aromatic azo derivative	MS	1 M HCl	-	WL,EIS	-	DFT
19	(-N=N-) heteroatoms	CS	Saline solution	94	WL,PDP,EIS	-	-
20	thiadizole- Azo	MS	1 M HCl	90	PDP,EIS	-	-
21	Azo derivative	MS	1 M HCl	-	WL	-	-
22	Azo- Schiff	CS	1 M HCl	-	EIS	-	-
23	(-N=N-) Pyrazole	CS	1 M HCl	93	PDP,EIS	-35	DFT
24	Green synthesis azo	CS	CO2-saturated NaCl solution	-	PDP,EIS	-	DFT
25	Selected dyes	MS	1 M HCl	96	WL,EIS,PDP	-33	DFT
26	organic inhibitor	CS	1 M HCl	-	PDP, EIS	-	DFT
27	Benzohydrazid derivative	MS	1 M HCl	-	EIS, EDX,SEM	-	DFT
28	Polymeric inhibitors	MS	1 M HCl	-	PDP, EIS	-	-
29	Triethanolamine	CS	1 M HCl	-	EIS, PDP	-	DFT

7. Comparative Analysis of Adsorption Behavior and Inhibition Performance

The reviewed studies consistently demonstrate that azo and azo–Schiff base derivatives exhibit inhibition efficiencies exceeding 90% in most acidic media [15–34]. A noticeable correlation can be observed between adsorption thermodynamics and electrochemical performance. Compounds exhibiting ΔG°ads values closer to −40 kJ mol□¹ generally demonstrate higher inhibition efficiencies and increased charge transfer resistance (R_{ct}), indicating stronger chemisorption contributions [15,18,30]. In contrast, inhibitors with ΔG°ads values closer to −30 kJ mol□¹ often display mixed adsorption behavior with slightly reduced efficiency under competitive ionic environments.

However this relationship should be interpreted with caution, as inhibition efficiency is also influenced by several additional factors, including acid type, steel

composition, inhibitor concentration, immersion time, temperature, and the electrochemical technique employed.

Therefore, adsorption free energy should not be treated as an isolated predictor of corrosion inhibition performance, but rather interpreted together with electrochemical and structural descriptors such as higher E_{HOMO} and lower ΔE values are frequently associated with improved inhibition efficiency, confirming that electronic properties strongly influence adsorption strength and film stability [21,27,42].

7.1.Sources of Variation in Reported Inhibition Performance

The variation in the reported inhibition efficiencies of azo-based corrosion inhibitors can be attributed to several interconnected factors. First, the acidic medium plays a major role in determining adsorption behavior and corrosion severity[16,17,18]. For example, inhibitors tested in HCl often show different performance from those examined in H_2SO_4 because sulfate ions may compete differently with inhibitor molecules at the metal/solution interface [19,23,24]. Second, the type of steel substrate also affects the observed efficiency, since mild steel and carbon steel may differ in surface composition, defect density, and oxide film behavior [15,16,28]. Third, molecular structure is another critical variable. Mono-azo and bis-azo compounds do not necessarily exhibit the same inhibition performance, because the number of azo linkages, planarity, electron density, and availability of adsorption centers all influence surface interaction[27,30]. In addition, differences in inhibitor concentration, immersion time, temperature, and electrochemical testing method may further contribute to discrepancies among published data. Therefore, direct comparison between studies should be made cautiously and always within the context of their specific experimental conditions[29,40]

7.2.Critical Evaluation of Adsorption Isotherm Models

Adsorption isotherm analysis is widely used in corrosion studies to interpret the interaction between inhibitor molecules and metal surfaces. Among the reported models, the Langmuir isotherm is the most frequently applied to azo-based corrosion inhibitors in acidic media because of its mathematical simplicity and its ability to provide a first approximation of adsorption behavior [19,23,28,30]. In many studies, a linear relationship between C/θ and C has been taken as evidence of Langmuir adsorption, suggesting monolayer formation and the absence of strong lateral interactions among adsorbed species [15,18,19].

However, the widespread use of the Langmuir model should be interpreted critically. The model assumes a homogeneous metal surface, identical adsorption sites, and no interaction between adsorbed molecules, conditions that are rarely fulfilled in real corrosive systems [21,40]. Steel surfaces exposed to acidic media are often heterogeneous because of surface defects, oxide remnants, local dissolution, and adsorption competition from aggressive ions such as Cl□ or SO□²□ [19,23,24,30]. Therefore, an apparently good Langmuir fit does not necessarily prove that the adsorption process is ideally Langmuir in a strict physicochemical sense [21,40].

Deviations from Langmuir behavior may arise from several factors, including surface heterogeneity, mixed physisorption–chemisorption contributions, multilayer tendencies, inhibitor aggregation, and competitive adsorption between inhibitor molecules and electrolyte ions [27,29]. In addition, temperature, concentration range, and the method used to estimate surface coverage (θ) may influence the apparent isotherm fit [17,19,26,30]. For this reason, adsorption constants and thermodynamic parameters derived from linearized models should be interpreted with caution and always within the limitations of the experimental design [21].

Compared with the Langmuir model, the Temkin isotherm may provide a more realistic description when interactions among adsorbed species are significant, while the Freundlich model can better reflect adsorption on energetically heterogeneous surfaces [40]. Although these alternative models are less frequently discussed in the reviewed azo-based inhibitor studies, their consideration is important, especially when the Langmuir plots show deviation, non-unity slopes, or limited linearity ranges [15,18,19 ,30]. Therefore, a critical comparison among Langmuir, Temkin, and Freundlich models would strengthen future corrosion inhibition studies and improve the reliability of adsorption interpretations [21,40].

7.3.Structure- Guided Design Principles for High- Performance Azo-Based Corrosion Inhibitors

A comparative evaluation of recent studies allows for the formulation of structure-oriented design principles for next- generation azo-based corrosion inhibitors. A consistent trend indicates that molecular structure critically controls adsorption strength and electrochemical stability[15,18,30].

First, the incorporation of multiple electron- donor centers, particularly in di azo derivatives and azo Schiff bases, significantly enhances inhibition efficiency. The presence of -N=N- double bonds or integrated azo-imine groups (-C=N-) also

increases the number of coordination sites available for interaction with vacant iron d orbitals, thereby strengthening chemosorption contributions and stabilizing the protective film [15,18,21,30].

Second, extended π coupling and molecular planarity promote better surface coverage through interactions of π-d orbitals with the steel surface[20,22]. Planar molecules with delocalized electron density generally exhibit lower energy gaps(ΔE) and higher EHOMO values, which facilitate electron donation and stronger absorption[21,27,42]. In many of the cases reviewed, inhibitors exhibiting ΔG° ads values approaching -40 KJ mol^{-1} and ΔE values below approximately 4eV were associated with inhibition efficiency exceeding 95%, indicating a synergistic relationship between thermodynamic and electronic indicators[22,41-43].

Third, the effects of substituents play a crucial role in the adsorption behavior. Electron donor groups such as -OH,-NH_2 and OCH_3 enhance electron density and promote stronger donor- acceptor interactions, while steric hindrance may reduce the packing efficiency on the steel surface[17,21,31]. Therefore, the balance between electronic optimization and structural coherence is a crucial factor in optimization.

Finally, the acidic medium itself affects adsorption mechanisms through proton equilibrium and the competitive adsorption of aggressive anions such as Cl-, which can modify the surface charge and adsorption direction[38,39,40]. Therefore, the rational design of inhibitors should consider both intrinsic molecular electronic properties and environmental conditions to ensure robust performance.

In general, the reviewed evidence suggests that future highly efficient azo inhibitors should incorporate multiple stabilization centers, extended coupling systems, improved molecular flattening, and electronically favorable substitutions to increase adsorption strength and long- term electrochemical stability.

8. Critical Limitations and Research Gaps

Despite the promising inhibition efficiencies reported for azo-based compounds, several limitations and research gaps remain. Most of the reviewed studies were conducted under controlled laboratory conditions using short immersion times and relatively simple acidic media, which may not fully represent complex industrial environments. Long-term stability, temperature fluctuation effects, and real-field applicability are still insufficiently investigated.

Additionally, although many studies reported adsorption thermodynamics and electrochemical parameters, a systematic correlation between molecular structure, adsorption strength, and industrial performance remains limited. Comparative studies

involving structurally related mono-azo and bis-azo derivatives under identical experimental conditions are still scarce.

From a theoretical perspective, while density functional theory (DFT) has been widely employed, advanced simulation approaches such as molecular dynamics (MD) under realistic solvent conditions are less frequently reported. Furthermore, environmental impact assessment and toxicity evaluation of azo-based inhibitors have received limited attention, despite their potential relevance for large-scale applications.

Future research should therefore focus on integrated experimental–theoretical approaches, long-term corrosion testing, and environmentally sustainable molecular design strategies to enhance practical applicability.

In addition to the conceptual limitations discussed above, several methodological inconsistencies can be identified in the studies reviewed. Despite the reported high inhibition efficiency, caution should be exercised when making direct comparisons between studies. Significant methodological differences exist in the experimental conditions, including immersion time, temperature, acid concentration, and surface preparation procedures. In some cases, ΔG° ads values are calculated using different adsorption models or without a clearly defined method for determining the equilibrium constant the method of determination, which may affect the thermodynamic interpretation[40,41]. Furthermore, inhibition efficiency values are sometimes compared across different media(HCl vs. H_2SO_4).

Without considering the differences in proton activity and competitive anion adsorption[38,39], these discrepancies highlight the need for standardized experimental protocols and standardized reporting criteria to improve reproducibility and strengthen the correlations between structure and performance.

9. Future Perspectives.

Future research on azo-based corrosion inhibitors should focus on bridging the gap between laboratory-scale investigations and real industrial applications. Most current studies are conducted under controlled static conditions; therefore, evaluation under dynamic flow systems, elevated temperatures, and varying acid concentrations is necessary to ensure practical applicability [18,24].

The integration of advanced computational modeling techniques with experimental validation represents an important direction. Combined density functional theory (DFT) and molecular dynamics (MD) simulations can provide more realistic prediction of adsorption behavior, solvent effects, and interfacial interactions [42–44]. Such multiscale approaches may significantly may contribute to the rational design of high-performance inhibitors.

In addition, the development of environmentally friendly and sustainable azo-based inhibitors is receiving increasing important. Future studies should emphasize green synthesis routes, biodegradability assessment, and toxicity evaluation to comply with evolving environmental regulations [45]. Incorporating renewable feedstocks and eco-compatible functional groups may improve the sustainability profile of these inhibitors.

Another promising direction involves the design of multifunctional hybrid systems that combine corrosion inhibition with antimicrobial or anti-scaling properties, particularly for oilfield and pipeline applications [23,28]. Moreover, systematic temperature-dependent thermodynamic studies and long-term immersion tests are required to better understand inhibitor stability and durability under harsh conditions. Overall, advancing azo-based corrosion inhibitors requires an integrated strategy combining molecular design, electrochemical validation, computational modeling, and environmental assessment.

10.Conclusions.

The collected studies clearly indicate that azo and azo–Schiff base derivatives represent an effective class of corrosion inhibitors for steel in acidic environments. Their performance is largely governed by molecular structure, particularly the presence of heteroatoms, conjugated π-systems, and auxiliary substituents that enhance adsorption stability. Thermodynamic analyses consistently show spontaneous adsorption behavior, while electrochemical measurements confirm the formation of protective surface films through increased charge transfer resistance and reduced corrosion current density. Although significant progress has been achieved, several aspects still require further investigation. Variations in adsorption parameters across different acidic media, limited long-term stability assessments, and insufficient integration between experimental and theoretical findings remain noticeable challenges. Future research should focus on correlating molecular electronic descriptors with adsorption thermodynamics under realistic operating conditions. In practice, inhibition efficiency is influenced by several experimental variables. Direct comparison between studies should therefore be approached with caution. Overall, a deeper understanding of structure–adsorption–performance relationships will support the rational development of more stable, efficient, and application-oriented azo-based corrosion inhibitors.

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