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Review Article

Corrosion inhibitors in drilling mud: Advances, challenges, and future Directions

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ABSTRACT

Corrosion remains a persistent challenge in drilling operations, particularly under high-pressure, high-temperature (HPHT) conditions, resulting in economic losses and safety risks. While conventional corrosion inhibitors have been effective to varying extents, their limitations, particularly in terms of toxicity, biodegradability, and compatibility with drilling fluid properties, necessitate exploring sustainable alternatives. Recent advances have focused on green inhibitors, notably plant-derived extracts, due to their biodegradability and low toxicity. However, a critical gap remains: few studies holistically evaluate both corrosion inhibition efficiency and the resultant impact on drilling fluid performance. To address this, the present review introduces an Integrated Screening and Corrosion Inhibition Modelling (I-SCIM) framework. This review comprehensively synthesizes recent research on corrosion inhibitors used in water-based, oil-based, and synthetic-based fluids. It categorizes inhibitors, evaluates their performance, and discusses their integration into complex mud systems. Key findings highlight that while conventional inhibitors achieve 70–85% efficiency, emerging green and hybrid formulations often exceed 90% inhibition. Furthermore, the paper explores the emerging class of smart and responsive inhibitors that adapt to environmental stimuli such as pH and temperature, highlighting their potential in dynamic wellbore conditions. By adopting the I-SCIM framework, this paper bridges the fragmented assessment approaches in current literature and proposes a unified strategy for evaluating corrosion inhibitors beyond inhibition efficiency alone. The review culminates in future research recommendations for inhibitors that are sustainable, efficient, and compatible with the evolving demands of HPHT drilling.

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1. Introduction

Corrosion, which is the deterioration of a metal, remains a critical challenge in the oil and gas drilling industry. Corrosion costs the US industries alone an estimated $170 billion every year (Brondel et al., 1994; Koch, 2017; Papavinasam, 2013; Popoola et al., 2013). Considering its complex and demanding production techniques, the oil industry takes an above-average share of these costs if any of its components fail. In drilling operations, corrosion significantly impacts well integrity, operational efficiency, and overall economics (Al-Shehri, 2019; Asrar, 2010; Bai et al., 2016; Cron and Marsh, 1983; Fayomi et al., 2019; Khodja et al., 2010; Popoola et al., 2013; Prasad et al., 2020). Under harsh downhole environments, drilling strings, casing, and tubulars are exposed to chemical and physical conditions that promote corrosion. The presence of dissolved oxygen, chlorine ions, hydrogen sulfide, and carbon dioxide is the primary cause of corrosion in drilling muds, which drives electrochemical reactions on metal surfaces (Askari et al., 2021; Brondel et al., 1994; Chilingar et al., 2008; Zhao et al., 2011). The reactions are usually cathodic processes, such as oxygen reduction and anodic dissolution, where iron is oxidized. The combined effect of these reactions results in the formation of

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corrosion products in the form of iron oxide or hydroxide (Galio and Dariva, 2014; Kadhim and Ali, 2017; Kadhim et al., 2021; Pavithra et al., 2012). These oxides either form a protective layer or result in continuous metal loss if unstable. The consequences of corrosion in the drilling industry are severe. It can lead to the loss of structural integrity, the thinning of casings, and the eventual failure of critical downhole equipment (AlGaiar and Afolabi, 2024; Brondel et al., 1987; Cirimello et al., 2017; Ibukun et al., 2024; Popoola et al., 2013; Yousuf et al., 2021). Not only does corrosion jeopardizes the safety of drilling operations, but it also results in non-productive time (NPT) and increased operational costs associated with repairs and replacements (Kadhim and Ali, 2017; Kadhim et al., 2021; Tamalmani and Husin, 2020). Additionally, its environmental impacts are significant, as corrosion-related failures and leaks can promote the release of hydrocarbons and drilling fluids into the surrounding ecosystem, potentially causing damage to humans and marine life (Agarwal et al., 2025; Jaramillo Clerque, 2022; Mubarak et al., 2023; Odeyemi and Alaba, 2024, 2025; Prasad et al., 2020; Singh and Singh, 2020; Solovyeva et al., 2023). Drilling fluids play an essential role in mitigating these corrosion-related challenges.

Drilling fluids account for 15–18% of the total drilling cost and must meet three important criteria: easy to use, not too expensive, and environmentally friendly (Al-Hameedi et al., 2020; Allison et al., 2019; Amanullah, 2007; Burke and Veil, 1995; Hossain and Al-Majed, 2015; Khodja et al., 2010). They are engineered to provide multiple functions: they cool the drill bit, stabilize the wellbore, transport drill cuttings, and, most importantly for corrosion control, act as a barrier between the corrosion environment and the metal surfaces (Akpan et al., 2024; Ball et al., 2012; Committee, 2011; Khodja et al., 2010; Lyons, 2009; Safian et al., 2024; Wang et al., 2013). These functions are performed simultaneously, indicating the sensitivity in designing drilling muds. When drilling muds are formulated, corrosion inhibitors such as amine-based compounds are added, and the muds adsorb onto the metal surface, forming a protective film that minimizes the exposure of the metal to corrosive agents. These corrosion inhibitors not only reduce the rate of corrosion but also help to maintain a stable pH, which further protects the steel from aggressive chemical attack (Chen et al., 2022; Kadhim et al., 2021; Khan et al., 2022; Km et al., 2024; Raja et al., 2016; Trabanelli, 2020; Yang, 2021). The result of using corrosion inhibitors is an improved drilling operation. The economic implications of effective corrosion management are commendable, as minimizing corrosion extends the life of the drilling equipment, reduces downtime, and lowers the overall cost of drilling operations (Bassey, 2017; Dubey, 2018; Galio and Dariva, 2014; Ghasemi et al., 2024; Guangyu, 2013; Ibukun et al., 2024; Islam and Hossain, 2020; Obot et al., 2023; Zhang, 2019).

This review paper aims to provide a comprehensive and critical synthesis of recent advances in the development and evaluation of corrosion inhibitors used in drilling mud systems, with a focus on both synthetic and green inhibitors published in recent years. A major gap identified in the current literature is the limited evaluation of the interactions between corrosion inhibitors and their effect on drilling fluid properties. While numerous studies have emphasized corrosion inhibition efficiency (IE%) in static and or electrochemical setups, only a few have assessed the inhibitor's performance in realistic drilling fluid environments, especially under HPHT conditions. This disconnect presents an opportunity to evaluate the impact of corrosion inhibitors on drilling fluid properties, thereby bridging the laboratory evaluation and field applicability. To address this gap, this paper is organized into several sections. Section 2 discusses the types of corrosion inhibitors used in drilling muds, including organic, inorganic, green, etc, and their inhibition mechanisms. Section 3 evaluates the laboratory techniques commonly used to assess corrosion inhibition performance, including weight loss, electrochemical impedance spectroscopy (EIS), and potentiodynamic polarization. Section 4 presents recent studies of corrosion inhibitors used in drilling fluid systems. Section 5 explores the underexplored area of how corrosion inhibitors affect drilling mud properties, including rheology, filtration, and stability. Section 6 introduces the emerging field of smart and responsive inhibitors, nanomaterials, and green inhibitors, highlighting their adaptive potential in wellbore conditions. Section 7 presents a comparative discussion and future outlook, proposing an Integrated Screening and Compatible Inhibitor Matrix (I-SCIM) for selecting multifunctional inhibitors based on both corrosion protection and mud performance compatibility. Section 8 highlights some challenges faced by corrosion inhibitors in drilling mud systems and concludes with recommendations for future research.

2. Classification and mechanism of corrosion inhibitors in drilling mud

The classification of corrosion inhibitors includes chemical nature, mechanism of action, environmental compatibility, and application methods. The choice of which inhibitor to employ depends on the environment, the material, and the operational conditions (Galio and Dariva, 2014). Organic inhibitors have been widely used in industries due to their versatility; however, green inhibitors are now being taken up as sustainable alternatives. Fig. 1 summarizes the classes of corrosion inhibitors.

2.1. Organic corrosion inhibitors

Organic corrosion inhibitors are used to reduce the occurrence of corrosion on metal surfaces by forming a protective film on the metal surface. They can either be amine-based, imidazoline-based or surfactant-based. Amine-based inhibitors contain one or more amine functional groups. They prevent and reduce corrosion either through adsorption on the metal surface, formation of protective complexes, or pH control (Khormali et al., 2025). Based on the availability of lone pair electrons on the nitrogen atom of the amine group, the molecules adhere strongly to the metal surface through the formation of covalent bonds with metal atoms. Such adsorption leads to the formation of a protective film, effectively isolating the metal from corrosive species (Loto et al., 2012). Amine-based inhibitors can form certain complexes with metal ions released during corrosion. Such complexes could further stabilize the surface and inhibit corrosion progression (Al-Amiery et al., 2023). In addition to forming protective films on metal surfaces, when used in drilling mud, amine-based inhibitors can

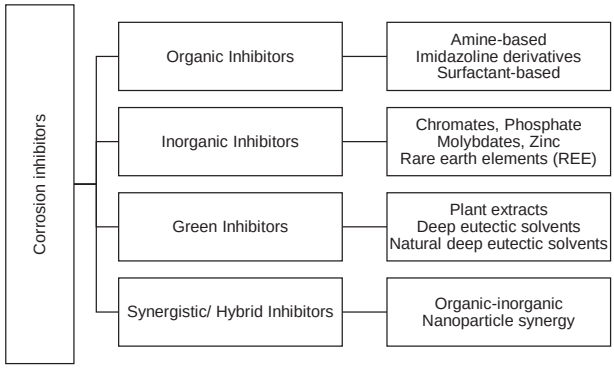


Fig. 1. Summary of the classes of Corrosion inhibitors.

help in maintaining the pH of the mud (Ahmed et al., 2024). A steady pH can prevent corrosion reactions, especially those connected with the evolution of hydrogen or dissolution of protective oxide layers, from occurring too slowly. While amine-based corrosion inhibitors are effective, they tend to foam excessively and are inconsistent during drilling operations (Ahmed et al., 2024). Furthermore, amine-based inhibitors are toxic and can pose an environmental hazard if not properly managed.

Imidazoline derivative inhibitors are synthesized through the corresponding reaction of fatty acids with polyamines under controlled environmental conditions (Ahmed et al., 2024). This reaction leads to the formation of an imidazoline ring, which can be substituted with long alkyl chains. These alkyl chains provide the inhibitors' hydrophobic properties that are useful in forming a water-repellent barrier on metal surfaces (Kadhim et al., 2021). The corrosion inhibition mechanism of imidazoline derivatives is adsorption on the metal surface and creation of a hydrophobic barrier. The imidazoline ring contains nitrogen atoms with lone pair electrons that can coordinate with the d-orbitals of metal atoms, resulting in strong adsorption on the metal surface (Wang et al., 2013). When adsorbed, the inhibitor molecules develop a compact hydrophobic barrier that physically occupies the entrance for corrosive agents to reach the underlying metal. The long alkyl chains in imidazoline derivatives extend away from the metal surface to create a hydrophobic barrier. This barrier repels water and solvent ions, thereby promoting the absence of the electrolyte necessary for corrosion reactions (Răuță et al., 2025). Imidazoline inhibitors prevent the anodic dissolution of metals and block cathodic reactions by physically covering the reactive areas (Kadhim et al., 2021). The long hydrophobic alkyl chain-based inhibitors exhibit extremely poor solubility in water-based systems, necessitating the use of emulsifiers or other formulation considerations for ensuring a uniform distribution (Wang et al., 2013). Although amine-based and imidazoline-based inhibitors inhibit corrosion by donating electron pairs from nitrogen atoms to vacant d-orbitals on iron, forming coordinate bonds and developing a hydrophobic film that reduces metal contact, the imidazoline ring structure enhances molecular rigidity and film compactness, resulting in superior thermal and shear stability compared to linear amines. Therefore, while the basic adsorption mechanism is shared, imidazolines exhibit distinct physicochemical advantages relevant to HPHT drilling-fluid applications (Jiashen and Jingmao, 1993; Osokogwu, 2012). Fig. 2 shows schematics of adsorption and film formation mechanisms for amine-based and imidazoline-based inhibitors.

Surfactant inhibitors are a unique subclass of organic substances which mainly inhibit corrosion due to their amphiphilic capabilities. Molecules belonging to such classes exhibit both hydrophilic and hydrophobic chemical functions (Ahmad et al., 2015). The existence of this unique action and structure leads to the formation of self-assembled protective films on metal surfaces to counteract the electrochemical reactions of corrosion (Abdelsattar et al., 2020; Ravi et al., 2025). The mechanism of inhibition for surfactant-based inhibitors is adsorption on the metal surface and the formation of a protective film (Abdelsattar et al., 2020; Ravi et al., 2025; Wang et al., 2023). Surfactant-based inhibitors feature hydrophilic heads capable of interacting strongly with metal surfaces (Ahmad et al., 2015). The spread of these inhibitors across the metal surface to form a continuous protective film results in a physical barrier which reduces the diffusion of corrosive agents to the metal surface (Tamalmani and Husin, 2020). The formed barrier affects local interfacial characteristics, such as surface energy and wettability, which in turn inhibit the electrochemical reactions responsible for corrosion by making the metal surface less accessible to the corrosive environment.

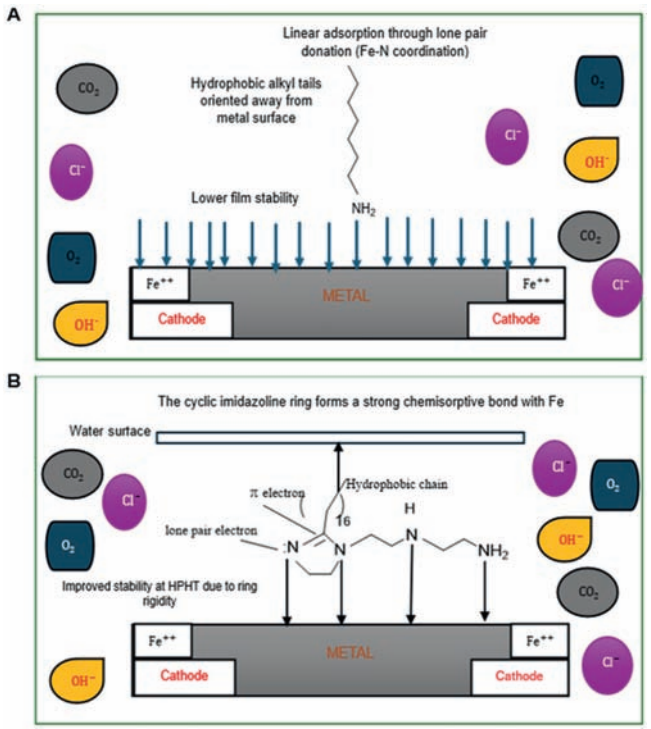


Fig. 2. Comparative schematic of adsorption and film formation mechanisms for amine-based (A) and imidazoline-based (B) corrosion inhibitors on steel surfaces under drilling-fluid conditions.

Surfactant-based inhibitors foam excessively within water systems (Ahmad et al., 2015). These inhibitors are largely non-biodegradable and have the potential to accumulate and negatively impact environmental health, particularly in sensitive marine and freshwater ecosystems (Yalman et al., 2022). At elevated temperature conditions, surfactant-based inhibitors will degrade and lose their protective properties. Fig. 3 shows a schematic mechanism of surfactant-based inhibtors.

2.2. Inorganic corrosion inhibitors

Inorganic corrosion inhibitors are usually salts or inorganic compounds that, when added to drilling muds, contribute towards forming protective films on metal surfaces or altering the local electrochemical environment capable of promoting corrosion rates (Bijapur et al., 2023). They interfere in the metal ion reactions or precipitate as insoluble films, thereby isolating the metal from

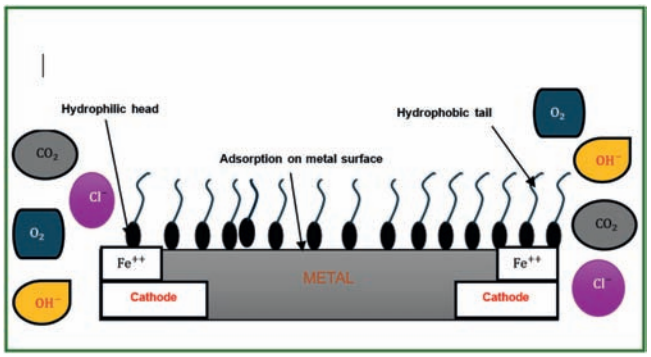


Fig. 3. Schematic mechanism of Surfactant-based inhibitor.

aggressive species in the drilling environment. They are usually in the form of chromate, phosphate or molybdate. Chromate inhibitors consist of chromium ions. These inhibitors have an action mechanism based on oxidation, where chromate ions act as oxidizing agents (Solovyeva et al., 2023). Such an oxidation reaction is centred on the transformation of the metal and results in a passivating protective film on the metal surface (Ahmed et al., 2024). Phosphate inhibitors consist of phosphate ions. In a drilling or acidic environment, ferrous ions released from the metal surface react with phosphate ions to form an insoluble iron phosphate compound. Molybdate inhibitors stem their corrosion inhibition from the presence of molybdate ions, which are mostly supplied by sodium molybdate. Molybdate inhibitors impede corrosion by forming a thin adherent film over the metal surface that also prevents the anodic and cathodic reactions (Ahmed et al., 2024). The molybdate ions react with the metal to produce insoluble molybdate complexes as a protective film (Bijapur et al., 2023). Inorganic inhibitors are toxic, non-biodegradable and non-environmentally friendly; hence, regulatory imposition on their usage. Fig. 4 shows a schematic mechanism of inorganic-based inhibitors.

2.3. Green and eco-friendly corrosion inhibitors

Eco-friendly green corrosion inhibitors are a sustainable alternative to traditional chemical inhibitors, used to reduce corrosion on metals while causing minimal environmental impact. These inhibitors are generally derived from renewable sources and are biodegradable with minimal toxicity (Shang and Zhu, 2021). Some organic corrosion inhibitors fall under this category of inhibitors. The sources of inhibition and biopolymers can be leaves, fruits, seeds, pericarp or other plant parts (Ahmad et al., 2015; Galio and Dariva, 2014; Miralrio and Espinoza Vázquez, 2020). The extraction methods of the bioactive compounds are enzymatic hydrolysis, heating reflux, Soxhlet, soaking, and ultrasonic extraction (Alrefaee et al., 2021; Badawi and Fahim, 2021; Shang and Zhu, 2021). Extraction temperature, drying temperature, extraction time, liquid-solid ratio, and the solvent used are among the factors that affect the extraction efficiency of the bioactive compounds from the plant (Dey and Kiran, 2022; Sheydaei, 2024).

Plant and bio-based extracts contain many active biopolymer compounds, including flavonoids, alkaloids, tannins, and saponins, which are rich in functional groups like amino, carboxyl, and hydroxyl (Ghehsareh et al., 2025). Such groups can adsorb onto the metal surface through physical or chemical bonding. The absorbed inhibition layer can shift the electrochemical potential of the metal, thereby reducing both anodic and cathodic reactions (González-Parra and Di Turo, 2024; Kartal et al., 2025). Ahmad et al. (2015) showed that multiple phenolic hydroxyl groups in tannins can chelate metal ions, forming a protective film that prevents further corrosion. In addition, many bio-based inhibitors create a continuous, adherent film on the metal surface (Al-Amiery et al., 2023; Palimi et al., 2023). The film functions as a physical barrier to hinder the access of corrosive species. Therefore, its integrity must be maintained as even a minor defect can lead to localized corrosion. Although plant extracts have shown promising corrosion inhibition at temperatures up to 120 °C, their stability under HPHT conditions is always compromised (González-Parra and Di Turo, 2024; Pial and Islam, 2025). At elevated temperatures, their bioactive compounds degrade, reducing their effectiveness and requiring additional stabilization measures. Fig. 5 shows a schematic mechanism of plant-based inhibitors.

As a type of green inhibitor, deep eutectic solvents (DES) are usually mixtures of two or more components, typically a hydrogen bond donor (HBD) and a hydrogen bond acceptor (HBA). They exhibit a phenomenon where their melting point is significantly lower than that of the individual components (Picchio et al., 2022). DES has been used in various applications, including extraction, catalysis, and electrochemistry (Acosta-Vega et al., 2025). When these components are derived from a natural substance, the resulting mixture is known as natural deep eutectic solvents (NADES). In addition to the benefits provided by DES, NADES also aligns well with sustainability goals due to their origin and enhanced biodegradability (Acosta-Vega et al., 2025). DES and NADES offer advantages such as biodegradability, cost-effectiveness, and low toxicity, making them attractive for use in harsh drilling environments (Picchio et al., 2022). DES and NADES prevent corrosion on metal surfaces by adsorption and film formation. DES/NADES molecules adsorb onto metal surfaces through hydrogen bonding and van der Waals interactions (Acosta-Vega et al., 2025). The functional polar groups, such as hydroxyl or carboxyl of DES/NADES, interact with the metal ions on the surface. When DES/NADES molecules are adsorbed on the metal surface, they develop an uninterrupted protective film that serves as a barrier against corrosive species. Studies from Picchio et al. (2022) have shown that NADES based on chlorine chloride and organic acids can increase the charge transfer resistance on the metal surface, thereby inhibiting corrosion processes. Although DES and NADES have indicated great promise as green corrosion inhibitors, at elevated temperatures, they tend to degrade, thereby losing their stability and efficacy in harsh environments. Additionally, their physical properties, such as viscosity, can influence their distribution in drilling mud (Acosta-Vega et al., 2025). Fig. 6 shows a schematic mechanism of DES/NADES inhibitors.

2.4. Mechanistic differences between plant-based and conventional corrosion inhibitors in drilling fluids

The main differences between plant-based and conventional synthetic corrosion inhibitors lie in their chemical composition, adsorption mechanisms, and film-forming behavior on metal surfaces under drilling fluid conditions. Although they both function primarily by forming an adherent protective layer that isolates the metal from the corrosive environment, the nature, strength, and stability of their films differ significantly depending on the type of inhibitor and its interaction with the drilling-fluid matrix.

Conventional inhibitors, such as amines, imidazolines, and organic salts, are typically single, ionic species designed for strong chemical interaction with steel surfaces. They often contain heteroatoms with available lone pairs that coordinate with Fe^{2+} ions to form chemisorbed films or protective complexes. The resulting films are usually compact, metallically bonded, and stable at high temperatures and pressures (Abdelsattar et al., 2020). In contrast,

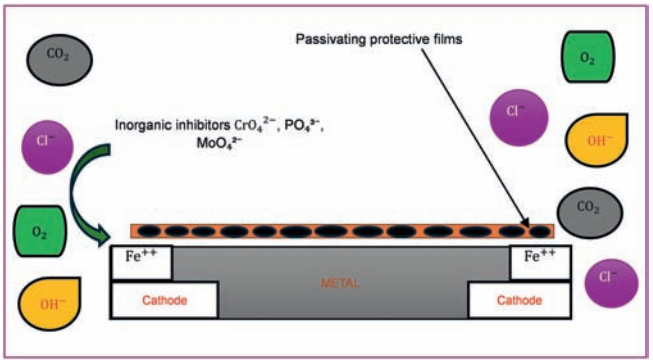


Fig. 4. Schematic mechanism of inorganic-based inhibitors.

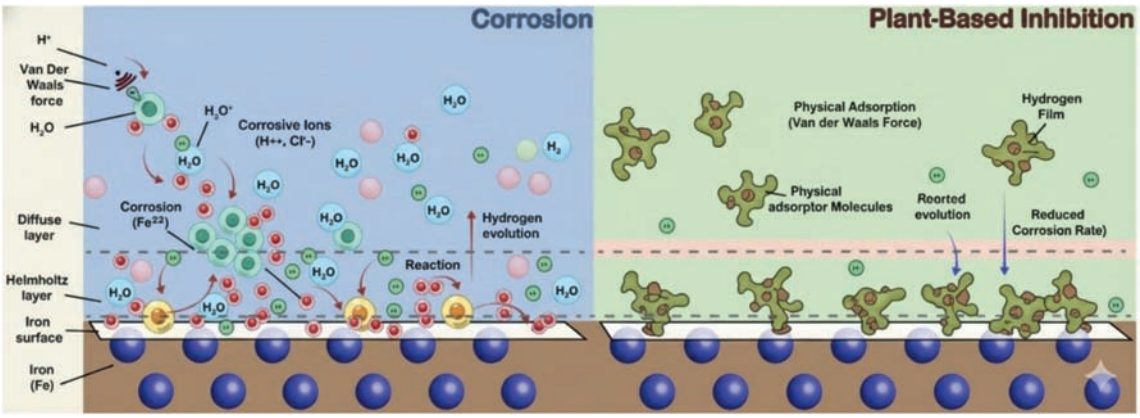


Fig. 5. Schematic representation of the mechanism for plant-based inhibition.

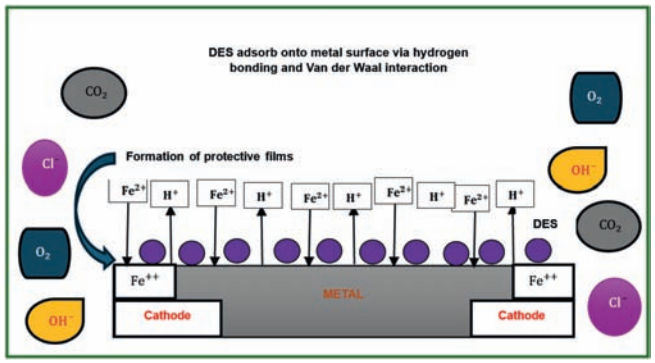


Fig. 6. Schematic representation of DES/NADES corrosion mechanism.

plant-based inhibitors are complex mixtures of organic compounds, such as polyphenols, polysaccharides, flavonoids and tannins, each containing functional groups like hydroxyl (–OH), carbonyl (C═O), carboxyl (–COOH), and amino ($–NH_2$) (Nadi et al., 2019; Valdez-Salas et al., 2021). These molecules adsorb mainly through physisorption, involving electrostatic attraction between protonated species and negatively charged steel surfaces, or through weak coordination with Fe atoms. Due to these extracts containing multiple constituents, the resulting inhibition is a synergistic effect of different molecular species rather than a uniform film produced by a single compound.

Conventional inhibitors predominantly exhibit chemisorption, where covalent or coordinate bonds are formed between the inhibitor molecule and surface metal atoms. This process is typically endothermic and yields highly stable films that can withstand mechanical stress and temperature fluctuations common in HPHT drilling operations (Jiashen and Jingmao, 1993; Osokogwu, 2012). Plant-based inhibitors, on the other hand, rely on physisorption and π-electron interaction from aromatic rings, supplemented by hydrogen bonding. These interactions, unlike conventional inhibitors, are exothermic and reversible, leading to less thermally stable adsorption layers (Ikram et al., 2021). Consequently, under HPHT or high-shear conditions, plant-derived films may degrade more rapidly.

Conventional inhibitors are known for their thermal and chemical robustness, maintaining inhibition efficiencies above 90% even at temperatures beyond 150 °C. However, they often pose toxicity and environmental persistence concerns, particularly in offshore discharges (Mainier et al., 2016). Conversely, plant-based inhibitors are biodegradable and environmentally friendly, but their thermal degradation temperature is typically lower than 130 °C. Polyphenolic compounds such as flavonoids can polymerize under high-temperature drilling conditions, resulting in diminished film integrity (Ghaderi et al., 2020). Therefore, their use in HPHT drilling requires stabilization through chemical modification or integration into hybrid systems to retain functionality. Table 1 summarizes the mechanistic differences between conventional inhibitors and plant-based inhibitors.

2.5. Nanoparticle-enhanced inhibition

Nanoparticles such as zinc, titanium, and cerium oxides can be dispersed within the inhibitor matrix to enhance the formation of a compact, adherent film on metal surfaces. The nanoscale dimensions of these particles allow them to fill micro-pores in the protective layer, reducing the permeability of corrosive species (Etsuyankpa et al., 2024). These nanoparticles can act synergistically with the different types of inhibitors. Polymer-nanoparticle composite, for instance, can exhibit improved thermal stability, mechanical strength, and corrosion inhibition efficiency compared to the polymer alone (Labouche and Parrott, 2013). Nanocomposites involve embedding nanoparticles within a polymer matrix, which is often derived from green sources. This kind of combination results in a material that possesses the desirable properties of both constituents, i.e. it possesses the flexibility and environmental compatibility of the polymer and the barrier properties of the nanoparticles. Etsunyankpa (Etsuyankpa et al.,

Table 1
Mechanistic difference between conventional synthetic and plant-based Inhibitors.

Mechanistic Feature	Conventional Inhibitors	Plant-based (Green) Inhibitors
Composition	Pure, well-defined compounds (amines, imidazolines, chromates)	Complex mixtures of organics (tannins, flavonoids, alkaloids)
Adsorption type	Predominantly chemisorption (Fe–N, Fe–S, Fe–O bonds)	Mainly physisorption with weak hydrogen bonding and π-electron interactions
Film characteristics	Uniform, dense, thermally stable monolayers	Multicomponent, less compact films; can degrade at HPHT
Thermal stability	Greater than 150 °C	Typically, less than 130 °C (Unless modified or crosslinked)
Environmental impact	Often toxic, non-biodegradable	Biodegradable, eco-friendly, but less durable

2024) demonstrated that a composite of chitosan with graphene oxide can enhance film formation and improve charge transfer resistance on steel surfaces. Although nanomaterials promise to be an improved technique for corrosion inhibition, achieving uniform dispersion of nanoparticles within the inhibitor matrix is critical. The Cluster of these particles can reduce the effective surface area and impede performance (Ahmad et al., 2015). In addition, the formulation of nanoparticles and nanocomposites is expensive, and scaling up these systems for industrial applications remains a huge challenge (Etsuyankpa et al., 2024). Fig. 7 summarizes the inhibition mechanisms of different inhibitors on metal surfaces.

Table 2 presents a comparison of various types of corrosion inhibitors, their inhibition mechanisms, and their limitations. We can observe from the table that synthetic corrosion inhibitors have technical limitations, such as pH sensitivity, the formation of foams in drilling muds, and compatibility issues with other mud additives. Moreover, they are toxic, non-biodegradable, and environmentally harmful, resulting in regulatory restrictions on their usage. On the other hand, green inhibitors, especially plant-based ones, although regarded as sustainable alternatives to synthetic inhibitors, are not thermally stable at high-temperatures and high-pressure conditions. Hence, limiting their use in these kinds of environments, which is predominant in recent offshore drilling operations.

3. Corrosion evaluation techniques

Evaluating corrosion inhibitors in laboratory settings is essential to determining their effectiveness, mechanisms, and suitability for specific environments. The selection and evaluation of corrosion inhibitors depend on the type of metal, the corrosive environment, and the desired level of protection (Arthur et al., 2013; Fateh et al., 2020; Ma et al., 2022). The assessment of corrosion inhibitors involves a combination of experimental and analytical techniques to assess their efficiency and mechanisms. The most used techniques include potentiodynamic polarization studies, electrochemical impedance spectroscopy (EIS), and weight loss measurements combined with surface characterization methods such as scanning electron microscopy (SEM), X-ray photoelectron spectroscopy (XPS), and atomic force microscopy (AFM). These methods either help quantify inhibition efficiency, analyze the protective film, or understand the electrochemical behavior of the inhibited systems (Yasakau, 2020).

Potentiodynamic polarization as an electrochemical technique is widely used to assess the performance of corrosion inhibitors and the corrosion behavior of metals. In this technique, the electrode potential is swept over a range of both cathodic and anodic regions, recording the resultant current density. Data obtained through this method provides insights into the kinetics of both anodic and cathodic reactions. These allow researchers to determine important parameters such as corrosion current density (E_{corr}), Tafel slopes, and corrosion potential (I_{corr}). The shape of the Tafel plot provides a mechanistic insight, revealing whether the inhibitor is predominantly anodic, cathodic, or mixed type, which is key for tailoring inhibition formulations. The potentiodynamic polarization method is particularly useful in drilling systems for evaluating how various inhibitors reduce corrosion by altering the electrochemical behavior at the metal-solution interface (Răuță et al., 2025). The results of potentiodynamic polarization are plotted as current density (log I) versus electrode potential (E) to generate a Tafel plot. The Tafel equation relates the overpotential (η) to the current density (I) in both anodic and cathodic regions.

$$\eta = a + b\log I \tag{1}$$

Where, η is the difference between the applied and the corrosion potential, E_{corr}, a is the constant related to the exchange current density, b is the Tafel slope, which is the difference between anodic and cathodic reactions, and I is the current density. Fig. 8 represents Tafel plots for mild steel in the absence and presence of different concentrations of 2-chloro-3-formyl quinoline in 1 M HCl solution at temperatures 303 K and 313 K.

Electrochemical impedance spectroscopy (EIS) is a robust, non-destructive evaluation method used to characterize the electrochemical behavior of metal surfaces in corrosive environments. The EIS technique measures the impedance of the metal-electrolyte interface to assess the protective properties of the inhibitor film (Ansari et al., 2022; Sharma et al., 2023). This method usually provides insight into the resistance and capacitance of the protective films formed by corrosion inhibitors, as well as the kinetics of the corrosion processes (Dehghani et al., 2019). EIS experiment is typically performed using a three-electrode cell, where the metal specimen acts as the working electrode, a reference electrode, such as silver, is used to maintain a constant potential, and a platinum counter electrode completes the circuit. The impedance is measured as a function of frequency. The resulting plot is a Nyquist: imaginary versus real impedance, or a Bode plot: impedance magnitude and phase angle versus frequency. The impedance of the system is expressed as a complex number:

$$Z(\omega) = Z'(\omega) + jZ''(\omega) \tag{2}$$

Where Z' is the real part, Z'' is the imaginary part, j is the imaginary unit, and ω is the angular frequency.

To interpret EIS data, a circuit is always modelled with an equivalent circuit that includes elements such as solution resistance (R_s), double-layer capacitance (C_{dl}), and charge transfer resistance (R_{ct}). A simple equivalent circuit can be represented as:

$$Z(\omega) = R_s + \frac{1}{\frac{1}{R_{ct}} \times jwC_{dl}} \tag{3}$$

Fig. 9 represents Nyquist plots for carbon steel in 1 M HCl containing different concentrations of Sargassum muticum extract (ESM) after 6 h of immersion at 303 K, and Fig. 10 represents Bode plots for carbon steel in 1 M HCl with various concentrations of inhibitors at 298 K.

Weight loss measurement, unlike the other electrochemical techniques, is a gravimetric method used to assess corrosion inhibitor performance by quantifying the actual material loss from a metal specimen over a specified period of exposure to a corrosive environment (Ansari et al., 2022; Zhao et al., 2011). This technique provides a direct measurement of the corrosion rate and the effectiveness of inhibitors in reducing material degradation. In this

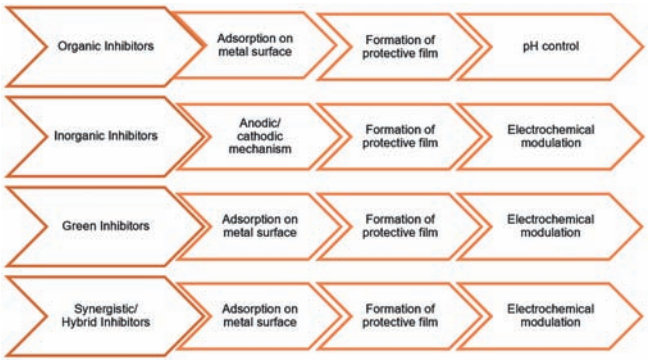


Fig. 7. Mechanism of action of different inhibitors on a metal surface.

Table 2
Comparison of the different types of corrosion inhibitors and their inhibition mechanism.

Inhibitors	Inhibition Mechanism	Limitations	References
Amine-Based Inhibitors	Excellent adsorption on metal surfaces through lone pair electrons, and forming protective films.	pH sensitivity, which can affect film stability.	(Ahmed et al., 2024) (Kadhim and Ali, 2017)
	Effective at reducing both anodic and cathodic reactions.	This may lead to foaming in drilling fluids.	
Imidazoline Derivative Inhibitors	Strong adsorption via the imidazoline ring and effective film formation.	Higher production cost due to complex synthesis.	(Ahmed et al., 2024)
	Low toxicity and good environmental profile.	Compatibility issues with other mud additives.	
Surfactant-Based Inhibitors	Form mixed-type inhibitors by adsorbing on metal surfaces via hydrophilic heads and forming hydrophobic barriers with alkyl chains.	Excessive foaming and emulsification may disrupt drilling operations.	(Ahmed et al., 2024; Kadhim and Ali, 2017)
	Effective in reducing both anodic and cathodic processes.	Environmental persistence if not biodegradable.	
Chromate Inhibitors	High inhibition efficiency through oxidation reactions, forming protective chromium oxide films.	High toxicity and carcinogenicity due to hexavalent chromium (Cr (VI)).	(Kadhim et al., 2021; Wang et al., 2013)
	Proven long-term performance in many applications.	Environmental and regulatory concerns.	
Phosphate Inhibitors	React with metal ions to form insoluble precipitates, creating a physical barrier.	Performance can be sensitive to pH fluctuations.	(Yahya et al., 2022)
	Effective in a range of pH conditions.	Sometimes, there is lower inhibition efficiency compared to other inhibitors.	
Molybdates Inhibitors	Form protective films and buffer-local pH, reducing corrosion rates.	Typically requires higher dosages and may be more costly.	(Asrar, 2010)
	Often used in combination with other inhibitors for synergistic effects.	Performance can depend on specific drilling fluid conditions.	
Zinc-Based Inhibitors	Affordable and effective, forming protective films through reactions with water and CO_2.	Sensitive to pH variations which affect film formation.	
	Lower toxicity compared to chromates.	Uniform dispersion in drilling fluids can be challenging.	
Rare Earth Element Inhibitors	Form robust, adherent oxide/hydroxide films on metal surfaces, effective in harsh HTHP environments.	High cost and limited availability.	(Hernández García et al., 2025)
	Superior stability and enhanced performance under aggressive conditions.	Complex formulation and dependency on fluid chemistry.	
Plant Extract/Bio-Based Inhibitors	Eco-friendly and biodegradable, derived from renewable resources.	Variability in composition and performance due to differences in plant source, extraction method, and seasonal changes.	(Dey and Kiran, 2022; Sheydaei, 2024)
	Often exhibit good inhibition efficiencies due to the presence of bioactive compounds like tannins, flavonoids, and alkaloids.	Lower thermal stability in HTHP conditions.	
Deep Eutectic Solvents (DES) Inhibitors	Offer tunable properties, low toxicity, and are biodegradable.	Often exhibit high viscosity, which may affect fluid properties.	(Picchio et al., 2022; Răuță et al., 2025)
	It can be engineered to optimize inhibition performance in specific environments.	Sensitivity to temperature and mixing conditions can affect performance.	
Natural Deep Eutectic Solvents (NADES) Inhibitors	Similar benefits to DES with the added advantage of natural, renewable components.	Limited research data and optimization studies compared to synthetic DES.	(Picchio et al., 2022)
	Enhanced biodegradability and environmental compatibility.	It may require further formulation improvements for industrial-scale applications.	
Hybrid Organic-Inorganic Inhibitors	Combine the benefits of both organic (film formation, adsorption) and inorganic (robust, passive films) inhibitors.	Formulation complexity and higher production costs.	(Bijapur et al., 2023; Zhou et al., 2022)
	Exhibit synergistic effects leading to superior inhibition performance under varying conditions.	Compatibility issues among diverse components can affect long-term stability.	
Nanoparticles and Nanocomposite Inhibitors	High surface area and ability to reinforce inhibitor films, resulting in enhanced barrier properties.	Dispersion challenges: Nanoparticles may agglomerate, reducing effectiveness.	(Etsuyankpa et al., 2024)
	It can fill micro-pores in the protective layer, reducing permeability to corrosive species.	Potential cost and environmental concerns related to nanoparticle synthesis and usage.	

method, metal coupons are weighed accurately and then immersed in a corrosive medium, such as simulated drilling fluid with and without inhibitors. After a predetermined time, the coupons are cleansed to remove corrosion products and re-weighed. The corrosion rate is then calculated as the difference in weight before and after the immersion in the inhibitor.

$$CR = \frac{87.6 \times W}{tAD} \tag{2}$$

Where A is the coupon area in cm^2, t is the exposure time in hours, D is the density of the coupon in gcm^{-3}, and W is the coupon's corrosion weight loss mg

The inhibition efficiency is thus calculated as:

$$IE\ (\%) = \frac{W_{blank} - W_{inhibited}}{W_{blank}} \times 100 \tag{3}$$

W_{blank} is the weight loss without the inhibitor and $W_{inhibited}$ is the weight loss with the inhibitor.

Scanning Electron Microscopy (SEM) is a characterization technique that enables the examination of surface morphology and composition of materials under high magnification. Essentially, it works by scanning a focused beam of electrons across a sample and detecting the interaction between electrons and the material, forming very detailed images with nanometer resolution.

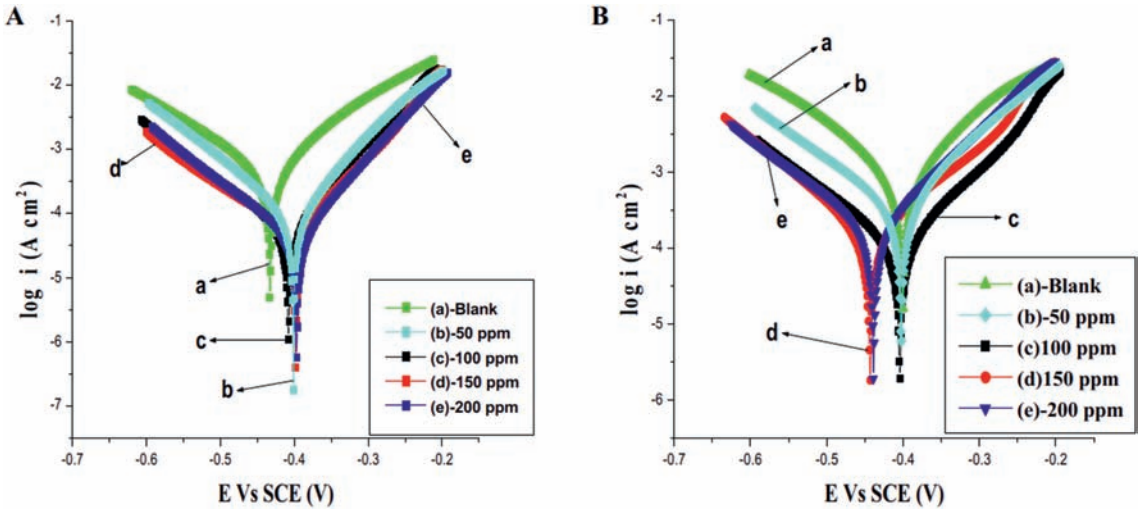


Fig. 8. *Tafel plots for mild steel in the absence and presence of different concentrations of 2-chloro-3-formyl quinoline in 1 M HCl solution at (A) 303K and (B) 313K* (Prasanna et al., 2016).

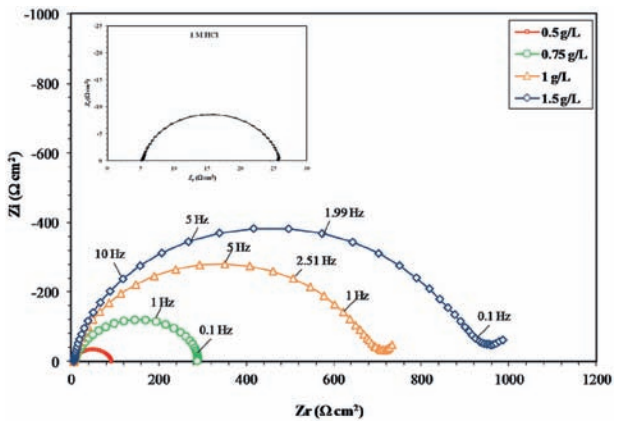


Fig. 9. *Nyquist plots for carbon steel in 1 M HCl containing different concentrations of ESM after 6 h of immersion time at 303K* (Nadi et al., 2019).

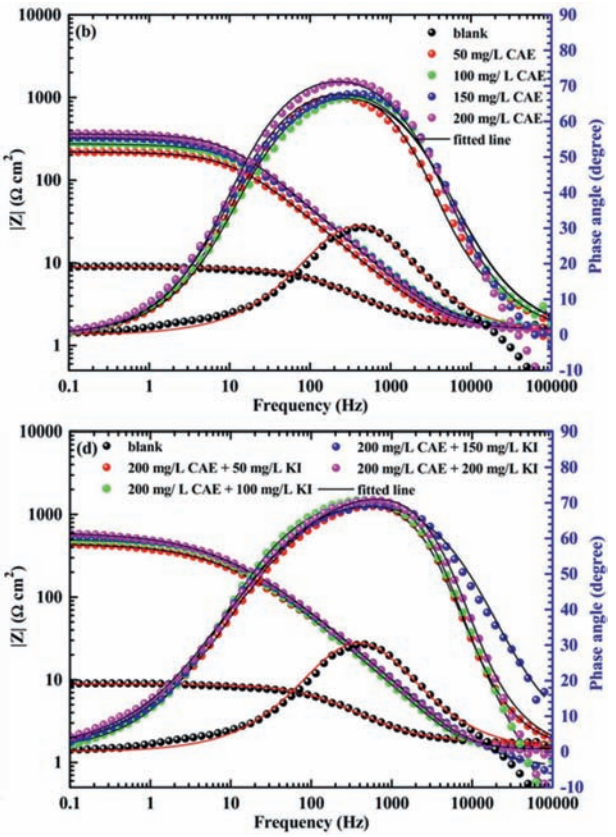
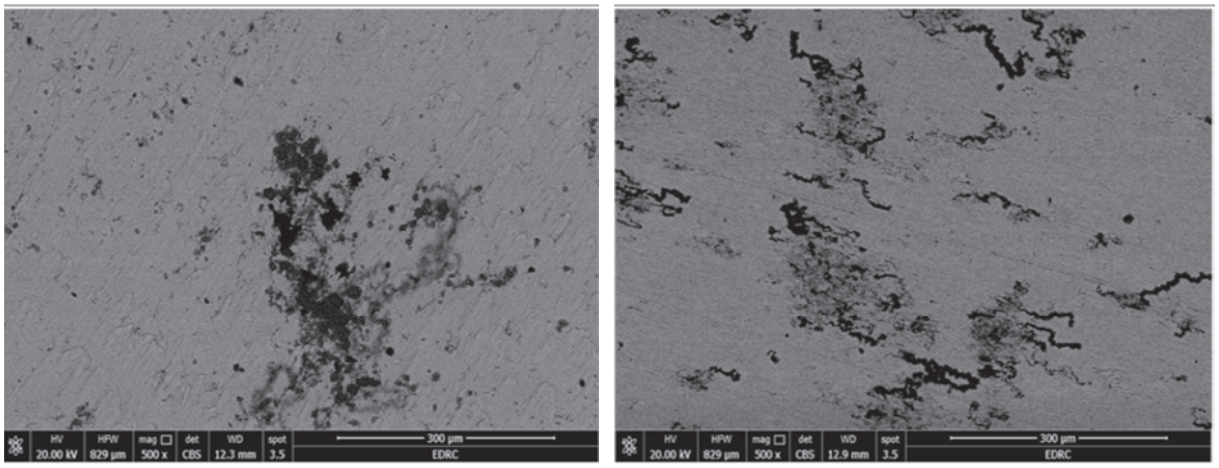


Fig. 10. *Bode plots for carbon steel in 1 M HCl with various concentrations of inhibitors at 298 K (Zhang* et al., *2025).*

SEM provides high-resolution images, down to a few nanometers; greater depth of field; and the ability to analyze the elemental composition of samples with energy-dispersive X-ray spectroscopy (Desimoni and Brunetti, 2015). Fig. 11 represents SEM images of low carbon steel in 10% HCl solution at 298 K in the absence of inhibitor, and in the presence of quaternary ammonium salt inhibitor.

X-ray photoelectron spectroscopy (XPS), unlike other characterization methods, provides very detailed information about the chemical composition and electronic structure of films or oxide layers formed over metals. Thus, XPS fits as a tool for understanding the protection mechanisms of corrosion inhibitors on metal surfaces, elucidating the passivity mechanism, and monitoring degradation processes (Desimoni and Brunetti, 2015; Sharma et al., 2023). XPS is mainly used in corrosion inhibition studies to analyze the thin surface films formed by inhibitors on metal surfaces. It can effectively identify the presence of organic inhibitor molecules, their oxidation products, and the formation of protective passive layers. Researchers can assess the efficiency of the inhibitor in mitigating corrosion by comparing spectra from treated and untreated samples (Lindsay and Thomas, 2022). The analysis of chemical interactions between the inhibitor molecules and the metal surface can be understood using XPS (Lindsay and Thomas, 2022). XPS can also help determine the thickness and uniformity of the inhibitor layer when combined with sputter depth profiling (Khan et al., 2022). Although XPS is a powerful tool, its inherent surface sensitivity typically probes only the top



(a) (b)

Fig. 11. SEM images of low carbon steel in 10 % HCl solution at 298 K (a) in the absence of inhibitor, (B) in the presence of quaternary ammonium salt inhibitor (Hamza et al., 2026).

1–10 nm, indicating that it may not represent the bulk properties (Ansari et al., 2022). Recently, atomic force microscopy (AFM) has become a fundamental tool for surface analysis at the nanoscale, due to its ability to provide high-resolution topographical images and quantitative mechanical data. By visualizing micro-to nanometer features of protective films, researchers can infer the uniformity, thickness, and integrity of the inhibitor layer, all of which are essential for effective corrosion protection (Hachem et al., 2025; Yasakau, 2020). AFM characterization provides direct imaging of the surface morphology of metal substrates treated with corrosion inhibitors. By correlating the surface morphology of untreated surfaces with the corresponding inhibitor-coated surfaces through AFM, researchers can observe alterations in surface roughness and the formation of passive layers and the homogeneity of an inhibitor film (Chen et al., 2020). AFM can also be used in force spectroscopy to measure mechanical variables: adhesion, elasticity, and stiffness of inhibitor films, which reveal how well the inhibitor has attached to the metal surface and its resistance to mechanical failure (Shinato et al., 2020). For accurate AFM analysis, the sample must be prepared meticulously, with the surface free from contaminants and ambient residues that might obscure the true morphology of the inhibitor film (Gowri et al., 2023; Shinato et al., 2020).

Table 3 presents inhibition efficiency values for multiple corrosion inhibitors tested using the standard weight loss, electrochemical polarization, and electrochemical impedance spectroscopy techniques previously discussed. We observe that in most studies, the EIS method yields slightly higher or comparable IE values than the weight loss or polarization techniques, indicating better surface passivation detection through impedance-based modeling. The inhibition efficiencies from polarization and EIS methods showed consistent performance trends, validating their reliability for short-term electrochemical analysis. Results from the weight loss method tend to lag slightly in inhibition efficiency, particularly at lower inhibitor concentrations, reflecting its sensitivity to average long-term degradation rather than instant electrochemical effects. We also observe that electrochemical techniques (polarization and EIS) are more responsive at low concentrations, making them suitable for initial screening. On the other hand, weight loss methods, while time-consuming, provide more conservative and realistic long-term data. In general, using all three methods provides a comprehensive assessment, allowing short-term and long-term perspectives. Across all studies, we observe that increasing inhibitor concentration correlates strongly with higher inhibition efficiency. For instance, Raviprabha et al. reported a 35% jump in inhibition efficiency when moving from 50 to 200 ppm. This validates Langmuir-type adsorption behavior, where monolayer formation improves with concentration. Although most studies were conducted at 303 K, Raviprabha et al. used 313 K, indicating that some inhibitors retain efficiency at elevated temperatures. It is worth noting that no investigation was carried out in HPHT conditions, highlighting a research gap that should be explored.

4. Corrosion inhibitors in drilling mud

Corrosion inhibitors play a crucial role as effective additives in drilling mud systems, where they help minimize the degradation of metallic infrastructure subjected to hostile downhole environments. Research in the offshore drilling industry has emphasized the importance of corrosion inhibitors in marine environments, where saltwater and high humidity exacerbate corrosion. These studies have explored the evolution of corrosion inhibitors and their performance in mitigating corrosion in drilling fluids. Abdelsattar et al. (2020) investigated the use of nanosized metallo-cationic surfactant complexes, such as CT-Zn, CT-Cu, and CT-Mn, which have demonstrated a high corrosion inhibition efficiency of 93.1% in static and dynamic conditions. Mainier et al. (2016) studied the application of sodium silicate as a non-aggressive, environmentally friendly corrosion inhibitor in saline drilling fluid. They discovered that it provided effective protection for carbon steel, especially in aerated environments, with inhibition efficiency greater than 92% at concentrations above 1250 mg/L. Benzotriazole has been studied by Xionghu et al. (2021) as a corrosion inhibitor in synthetic-based drilling fluids. It demonstrated excellent lubricity and corrosion inhibition properties, reducing the coefficient of friction by up to 95.93%. Algburi (2023) evaluated the efficiency of green corrosion inhibitors, such as corn oil, sunflower oil, flaxseed oil, and castor oil, for their effectiveness in crude oil environments. These inhibitors showed inhibition efficiencies ranging from 41.85% to 92.63% at a concentration of 400 ppm. Alanazi et al. (2023) developed and evaluated dual-purpose corrosion and kinetic hydrate inhibitors based on 3-acrylamidopropyl trimethyl ammonium copolymers. These inhibitors provided corrosion inhibition efficiency of up to 90% and are effective in sour environments. Table 4 shows various corrosion inhibitors and their performance in drilling mud systems.

Table 3
Different laboratory evaluation techniques for corrosion inhibitors and their performance.

					Weight loss method	Electrochemical Polarization measurement	Electrochemical Impedance Spectroscopy measurement	Ref.
Inhibitor	Temp (K)	Coupon	Medium	Conc. (ppg)	I E (%)	I E (%)	I E (%)	
5 ((6-Methyl-2-oxo-2H-chromen-4yl) thiomethyl)-2 ((N-(3-methyl quinoxalin-2(1H) one) yl) methyl)-1,3,4-oxadiazole	303	Mild steel	0.5 M HCl	10	71.03	72.69	72.69	(Dehghani et al., 2019)
				50	83.93	84.85	84.85	
5 ((6-Methyl-2-oxo-2H-chromen4yl) thiomethyl)-2 ((N-(3-methyl-quinoxalin-2(1H)-one) yl) methyl) 1,3,4oxadiazole	303	Mild steel	1 M HCl	10	71.03	72.69	72.69	(Pavithra et al., 2012)
				50	83.93	84.85	84.85	
2-chloro 3-formyl quinoline	313	Mild steel		50	52.38	52.38	66.03	Prasanna et al. (2016)
				0				
				200	88.22	85.03	85.34	
Rabeprazole sulfide	303	Mild steel	0.5 M H_2SO_4	0.05	80.4	89.81	72.32	(Shanbhag et al., 2011)
				1	98	98.25	95.09	
(RS)-2-4- [2- Hydroxy-3-(propan-2-ylamino) propoxy] phenyl acetamide)	303	Mild steel	1 M HCl	100	61.4	69.3	79.9	(Raviprabha and Bhat, 2023)
				350	92.8	93.8	92.5	
Acetyl coumarine	303	Zinc	0.1 M HCl	0.63	42	38	39	Minagalavar et al. (2023)
				5	85	83	89	
[2-(2,4-Difluorophenyl)-1,3-bis (1H-1,2,4- triazol-1-yl) propan-2-ol]	300	Mild Steel	0.5 M H2SO4	10	88.08	68.63	72.14	(Karthik and Sundaravadivelu, 2016)
				110	93.61	91.06	90.24	
Bromo acetyl coumarine	303	Zinc	0.1 HCl	0.63	57	55	49	(Minagalavar et al., 2023)
				5	97	94	89	
4- [4-(6,8-bromo-2-oxo-2H-chromen-3-yl) thiazol-2-yl amino]-methyl -7-chloro-1H-quinoline-2-one	303	Zinc	0.1 M HCl	0.63	44	43	43	
				5	92	88	86	
4- [4-(6-bromo-2-oxo-2H-chromen-3-yl) thiazol-2-yl amino]-methyl -8-methyl-1H-quinoline-2-one	303	Zinc	0.1 M HCl	0.63	44	43	43	
				5	92	88	86	

The Table summarizes representative corrosion inhibitors tested in drilling mud or drilling-relevant environments, highlighting a wide diversity of formulations ranging from nanometal complexes and inorganic salts to green bio-extracts and organic surfactants. Collectively, these studies report inhibition efficiencies of 80–90 %, suggesting significant potential for both synthetic and naturally derived systems. A closer examination of the table shows that green and hybrid formulations generally outperform conventional alternatives. Notably, PEG-2 oleamide blends and saffron petal extract inhibitors demonstrated efficiencies of 99.7% and 96.5% respectively, surpassing even well-established surfactant-metal complexes (CT-Zn/Cu/Mn, 93.1%) and imidazoline-based compounds (90%). Fig. 12 presents a graph of inhibition efficiency and concentration for various corrosion inhibitors used in different drilling fluid systems.

While results highlight that green and hybrid formulations offer promising eco-friendly performance, the operational context (mud type, temperature, metal type) must guide the final selection of the inhibitor. The integration of rheological assessment with electrochemical and gravimetric techniques will enable optimal formulation and deployment under field conditions. As observed from the data in the table, a positive trend exists where higher inhibitor doses tend to give higher inhibition efficiencies. For example, 300 ppm of CT-Cu complex yielded 93.1% efficiency, whereas a lower concentration of 200 ppm for CT-Mn complex yielded only 88.5%. Fig. 13 shows a graph of different inhibitor concentrations against inhibition efficiency, highlighting the strong correlation between inhibition efficiency and concentration (extracted from Table 4 and Abdelsattar et al. (2020))

We can also see that different inhibitor classes show distinct performance clusters. Nanometal complexes achieved an inhibition efficiency of 93.1% indicating that the metallic centre significantly influences adsorption strength and film compactness. These findings provide strong evidence that metal-surfactant complexes can form dense, adherent protective layers on carbon steel. Yet, the experiments were conducted under static conditions, and the stability of these films under high-shear or HPHT circulation remains uncertain. Furthermore, although the copper-containing complex provided the greatest protection, it also increases ecotoxicological risks and cost concerns. Inorganic and nanomaterial inhibitors provided passive, oxide-based barriers rather than adsorbed organic layers, with inhibition efficiencies of 85–92% confirming that inorganic nanoparticles can enhance surface passivation in WBM systems. However, dispersion stability remains a persistent issue; agglomeration within bentonite suspensions can reduce active surface area, while long-term mud storage may initiate sedimentation and inconsistent dosing. Organic surfactants and amine-based inhibitors continue to show effective inhibition of 88–92%, confirming the reliability of these traditional chemistries. Imidazoline remains ideal for CO_2 and H_2S-bearing environments due to its film-forming capability and thermal tolerance. Nonetheless, these systems rely on petrochemical feedstocks and can pose environmental and emulsification issues, motivating the transition toward green or hybrid inhibitors. Green and bio-based inhibitors demonstrated high inhibition efficiencies of 91–99.7% in various aqueous or crude-oil media. These results underline the strong adsorption potential of polyphenolic and oxygen-rich biomolecules. The collective data in Table 4 highlight a clear methodological gap; none of the studies integrated HPHT aging or flow-loop simulation in their corrosion evaluation. Furthermore, few works correlated corrosion performance with changes in mud rheology and filtration, even though

Table 4
Corrosion inhibitors in drilling muds and their inhibition performance.

Inhibitor	Classification	Conc.	Medium	Specimen	IE (%)	Experimental evaluation	Ref.
CT-Cu	Nanometal complex	300 ppm	WBM	Carbon steel	93.1	Potentiodynamic polarization, Weight loss methods	(Abdelsattar et al., 2020)
CT-Zn	Nanometal complex	300 ppm	WBM	Carbon steel	90.8		
CT-Mn	Nanometal complex	200 ppm	WBM	Carbon steel	88.5		
Sodium Silicate	Inorganic	2000 mg/L	WBM	Carbon steel	92	Gravimetric tests, Electrochemical impedance	Mainier et al. (2016)
Castor Oil	Green	400 ppm	Crude Oil	Carbon steel	92.63	Weight loss methods	Algburi (2023)
Benzotriazole		80:20 ratio with mineral oil	SBM		95.93	Hot rolling oven at 150–170 °C	(Xionghu et al., 2021)
Imidazoline	Organic	1000 ppm	H_2S, Co_2		92	High-speed Autoclave Test (HSAT) for evaluation	(Osokogwu, 2012)
Purple sweet potato	Green	200 mg/L	Stratum water environment,	N80 steel	91.38	Potentiodynamic polarization, Weight loss methods	Zhang and Feng (2025)
Saffron Purple Petals (SPP)	Green, Organic	3 wt%	Bentonite-based	Mild Steel	96.50	Potentiodynamic polarization, Electrochemical impedance	Ghaderi et al. (2020)
VE60	Nonionic surfactant	5000	WBM	Carbon Steel	88.7	Potentiodynamic polarization at 25 °C	Negm et al. (2015)
PEG-2 Oleamide, Glycerol Myristate, Glycerol Linoleate	Green, Fatty Acid-Based		Emulsion-based	Carbon Steel	99.7	Electrochemical measurements, SEM, EDS, XPS	Palimi et al. (2022)
ROS	Natural oil extract	10,000	WBM	Mild Steel	80	Potentiodynamic polarization at 25 °C	Loto and Busari (2020)
Imidazoline (I_m-B)	Organic	2000	H_2S-bearing drilling mud	40 Cr steel	50	Potentiodynamic polarization at 25 °C	Jiashen and Jingmao (1993)
Limonite Pigment	Organic	4 lb	WBM	API N80 steel	0.058 mm/y	Weight loss method	Oni et al. (2025)
Zn Fe_2O_2, $Zn_{0.6}Ni_{0.4}$ Fe_2O_2	Nanomaterial	50 ppm	WBM	Carbon Steel	0.77 ± 0.2 mpy	Weight loss method	(Al-Rubaiey et al., 2017)
Calcinated nano-ferrites	Nanomaterial	50 ppm	WBM	Carbon Steel	0.69 ± 0.20 mpy		
Molybdate-based	Inorganic	0.12% mass fraction	WBM	G105 steel	85	Electrochemical impedance, Weight loss method	
Prosopis farcta powder	Green	15 ppb	WBM	API 5LX70	0.0029 mm/year	Weight loss method	Jaf et al. (2023)

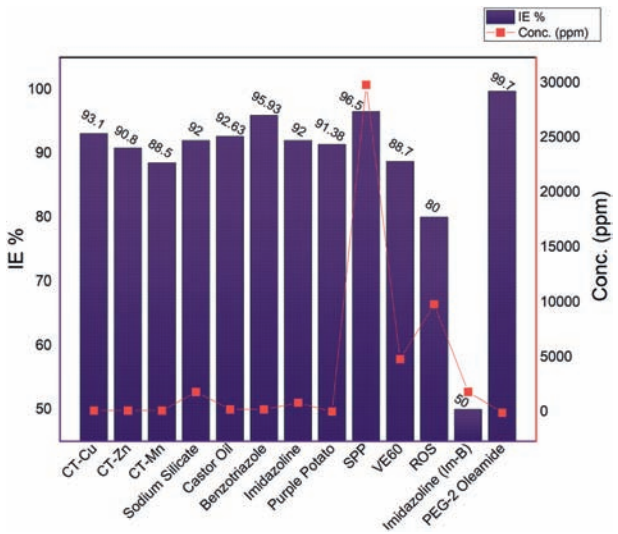


Fig. 12. Corrosion inhibition efficiency of selected corrosion inhibitors in drilling mud systems. Values reflect reported experimental performance from literature sources compiled in Table 4.

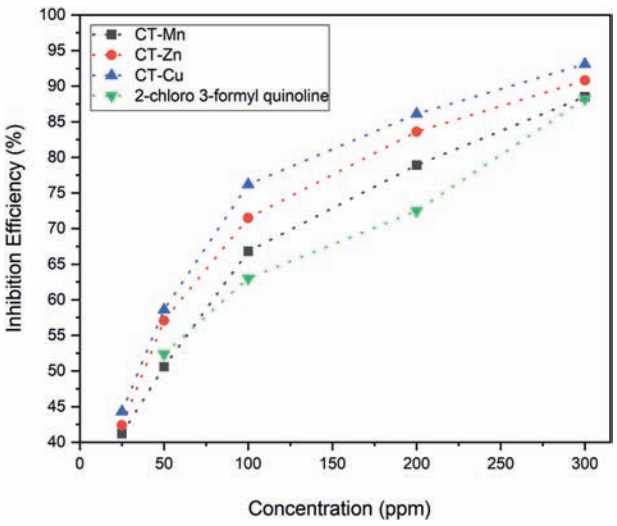


Fig. 13. Concentration of inhibitors (CT-Mn, CT-Zn, CT-Cu, 2-chloro-3-formyl quinoline) against inhibition efficiency.

these properties determine practical viability.

5. Impact of corrosion inhibitors on drilling fluid properties

The addition of corrosion inhibitors to drilling fluids is primarily intended to mitigate the degradation of metal components during drilling operations. However, it is equally critical that these inhibitors do not adversely affect the functional properties of the drilling mud, which must continue to meet performance standards essential for effective wellbore stability, cuttings transport, and pressure control. With the growing interest in plant-based and environmentally friendly corrosion inhibitors, it becomes imperative to assess their influence on key drilling fluid parameters to ensure continued compliance with API specifications. Despite the increasing development and application of corrosion inhibitors, particularly green alternatives, relatively few studies have systematically evaluated their impact on drilling fluid properties. This highlights a significant gap in the literature and underscores the need for further research focused on the comprehensive assessment of these additives within drilling fluid systems.

Abdelsattar et al. (2020) in their studies reported that adding 300 ppm of CT-Cu, CT-Zn, and CT-Mn nanometal complexes to a bentonitic WBM caused only slight changes in viscosity. The plastic viscosity (PV), apparent viscosity (AV) and yield point (YP) of the mud were measured before and after the addition of the inhibitor. The bar chart in Fig. 14 shows that PV and YP rise only marginally with inhibitors, and AV changes little, all within acceptable API limits (Abdelsattar et al., 2020).

In other words, these inhibitors did not negatively affect the rheological properties of the mud. The gel strength and thixotropy were also slightly increased after adding the nanometal inhibitors, remaining compatible with drilling specifications (Abdelsattar et al., 2020). Fig. 15 shows the gel

strength and thixotropy properties of the prepared WBM before and after the addition of the successful 300 ppm concentration of the inhibitors, which gave a high corrosion inhibition efficiency.

The effect on fluid loss is also generally small or positive. Abdelsattar et al. (2020) reported that adding 300 ppm nanometal inhibitors produced a slight decrease in API fluid loss. Fig. 16 compares the filtrate volume after a 30-min API filter press, before and after adding the inhibitor. A modest reduction was observed in the filtrate and cake volume after inhibition (Abdelsattar et al., 2020). Overall, the prepared mud with the nanometal complexes met API filtration standards. This result suggests that the adsorbed inhibitor molecules can help form a slightly denser filter cake.

Ghaderi et al. (2020) reported that incorporating Saffron Purple Petals (SPP) powder into a bentonite base mud resulted in a distinctive filtration behavior. The volume of the filtrate gradually

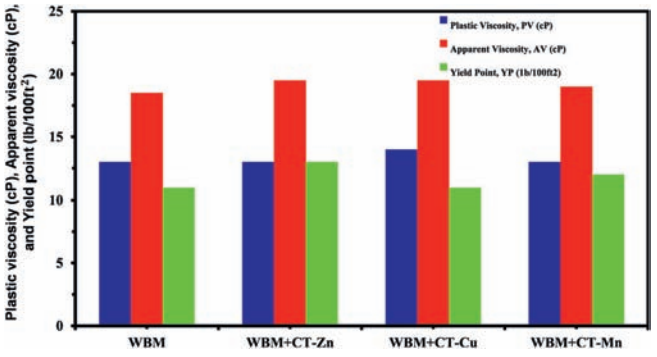


Fig. 14. *Rheological properties of the prepared WBM before and after the addition of the successful concentration of the inhibitors (CT-Zn, CT-Cu, and CT-Mn)* (Abdelsattar et al., 2020).

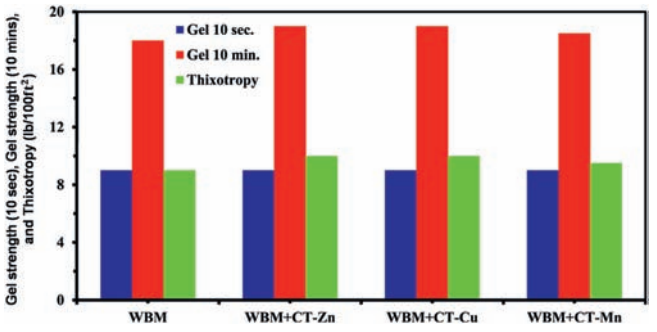


Fig. 15. Gel strength and thixotropy of the prepared WBM before and after the addition of the successful concentration of the inhibitors (CT-Zn, CT-Cu, and CT-Mn) (Abdelsattar et al., 2020).

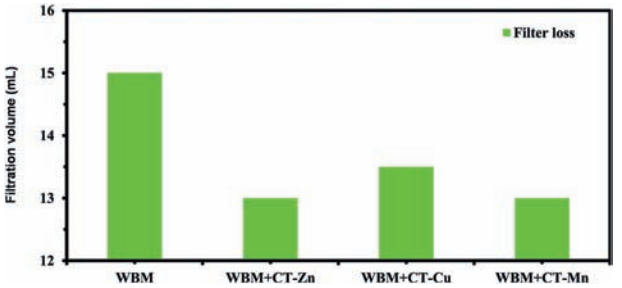


Fig. 16. Filter loss of the prepared WBM before and after the addition of the successful concentration of the inhibitors (CT-Zn, CT-Cu, and CT-Mn) (Abdelsattar et al., 2020).

reduced as the SPP powder content increased from 1 to 3 wt% (Ghaderi et al., 2020). The muds with 1, 2, and 3 wt% SPP powder had filtrate volumes of 20, 16.6, and 14.4 mL, demonstrating a decrease of 23.7, 36.6, and 45% in the volume of the filtrate (Ghaderi et al., 2020). This result indicates that the addition of SPP powder to the mud yields a significant improvement in mitigating filtration volume. Fig. 17 shows filtration results for the prepared base mud and muds containing 1, 2, and 3 wt% SPP powder.

Plant-based corrosion inhibitors are gaining increasing attention due to their biodegradability, availability, and environmental compatibility. These green inhibitors typically contain bioactive compounds, such as polyphenols, flavonoids, and polysaccharides, which enable them to adsorb onto metal surfaces and form

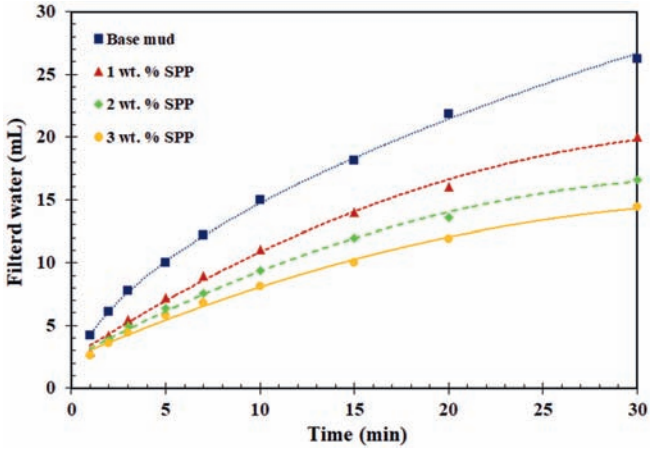


Fig. 17. Filtration results for the prepared base mud and muds containing 1, 2, and 3 wt% SPP powder (Ghaderi et al., 2020).

protective films that hinder electrochemical reactions responsible for corrosion (Rani and Basu, 2012). In addition to corrosion inhibition potential, several plant-based additives have demonstrated the ability to enhance the rheological properties of drilling fluids. For instance, Ismail et al. (2020) demonstrated how Henna leaf extract, rich in tannins and phenolic compounds, can improve viscosity and gel strength, thereby enhancing cuttings transport and reducing fluid loss. This suggests that such plant-based materials may offer dual functionality, serving simultaneously as corrosion inhibitors and rheological enhancers in water-based mud systems. However, a critical review of existing literature reveals that most studies tend to evaluate only one aspect of these bio-additives, either focusing on their corrosion inhibition efficiency or their influence on rheology, without investigating both roles simultaneously. This presents a notable gap and an opportunity for further exploration into the multifunctional performance of green inhibitors in drilling fluid formulations.

During drilling operations, the corrosiveness of the environment and the effectiveness of inhibitors are determined not by any single variable but by the combined action of several factors, like temperature, dissolved gases, ionic strength, hydrodynamics, substrate metallurgy, and drilling fluid composition. Laboratory screening that fails to account for these interacting factors risks producing inhibitors that will fail downhole or promote false chemistries. Below, we examine each major driver and give practical recommendations for robust testing.

5.1. Temperature and mud composition

The kinetics of corrosion inhibitor adsorption, desorption, and degradation are critically influenced by temperature. Elevated downhole temperatures accelerate both anodic and cathodic reactions, hence reducing inhibitor film stability through desorption or thermal decomposition (Al-Amiery et al., 2023). Organic inhibitors containing heteroatoms (O, N, S) often lose their efficiency above 130 °C due to volatilization or structural rearrangement (Sheetal et al., 2023). In contrast, nanocomposite and crosslinked polymeric inhibitors exhibit enhanced stability, maintaining compact film morphology and charge-transfer resistance at HPHT conditions (Abdelsattar et al., 2020; Gokapai et al., 2024). While multiple reviews emphasize that inhibitor performance measured at ambient conditions is a predictor of HPHT performance, HPHT electrochemical tests often reveal a rapid loss of film integrity above 120–150 °C (Askari et al., 2021). Therefore, any meaningful corrosion evaluation for downhole use must include HPHT aging, followed by electrochemical and weight-loss testing under representative pressure-temperature conditions.

5.2. Water-based vs oil-based muds

Corrosion susceptibility varies significantly with the continuous phase. Water-based muds (WBMs) readily dissolve oxygen and carbon dioxide, promoting uniform corrosion, whereas oil-based muds (OBMs) form a hydrophilic barrier that limits oxygen ingress (Zheng, 2020). Nevertheless, emulsified water droplets in OBMs can localize corrosion, particularly in high-clay or poorly stabilized emulsions (Alkalbani and Chala, 2024). Therefore, inhibitors must be phase-compatible; polar inhibitors such as imidazolines for WBMs and amphiphilic surfactants or organophosphorus compounds for OBMs (Zhu et al., 2017; Zhuang et al., 2021).

5.3. Metallurgy of casing and drill collars

The metallurgical composition of casing joints and drill collars determines base electrochemical behavior and passive film chemistry, which affect inhibitor efficiency. Inhibitors optimized for carbon steel may perform poorly on Cr-rich alloys or in mixed-metal assemblies due to changes in adsorption energetics and galvanic coupling. Carbon steels corrode actively in a chloride-rich drilling environment, while Cr–Ni–Mo alloys display enhanced passivation (Li et al., 2019). We recommend that corrosion screening be performed on the actual alloys or a representative set. Recent studies by Davydov et al. (2023) showed that 13 Cr and duplex steels exhibit distinct passivation and scale formation behavior in formate and chloride environments, which is important for inhibitor selection in HPHT completion fluids.

5.4. Effect of dissolved gases (O_2 and CO_2.) and salinity

Oxygen dissolved in drilling muds acts as a cathodic depolarizer and directly improves the overall corrosion current even at small ppm levels (Bertness et al., 1989). Oxygen ingress also complicates the interpretation of electrochemical screening. To suppress oxygen-driven corrosion, oxygen scavengers such as sodium sulfide and hydrazine derivatives are often incorporated into WBM in synergy with film-forming inhibitors. Carbon dioxide, in contrast, increases acidity through the formation of carbonic acid, which enhances general corrosion and localized pitting under specific conditions (Retnanto et al., 2024). Studies that fail to report dissolved oxygen and carbon dioxide or that test only deaerated solutions, therefore, cannot be directly translated into field practice.

High chlorine concentration increases solution conductivity and disrupts protective oxide or inhibitor films, promoting localized pitting and undermining sacrificial precipitation mechanisms. While the bulk effect of salinity is often reported qualitatively, its interaction with pH, temperature, and inhibitor chemistry is nonlinear and sometimes counterintuitive. Therefore, we recommend that testing across the expected salinity range of the targeted field should be mandatory. Comprehensive reviews and experimental studies emphasize that chlorine sensitivity must be quantified by cyclic polarization/pitting tests and that inhibitors that function in low chlorine brines may fail in high-TDS drilling fluids (Eliaz, 2019).

5.5. Hydrodynamic effects (flow rate, shear)

Circulating drilling fluids impose shear and turbulence that mechanically remove loosely adsorbed inhibitor films as well as increase mass transport of corrosive species to the metal surface. Galvan-Martinez et al. (2007) demonstrated that under turbulent flow, corrosion rates double compared to static conditions. The protective efficiency of adsorbed inhibitors decreases at Reynolds numbers above 10^4 due to the mechanical removal of the adsorbed layer. Static laboratory electrochemical tests, such as static polarization, systematically under-predict corrosion under flow. Dynamic methods, such as the Rotating Cylinder Electrode (RCE), rotating cage, tribo-corrosion rigs, or flow-loop testing, reproduce shear-induced film stripping and allow quantification of shear thresholds at which inhibitors fail. Hydrodynamic experiments reveal that some film-formers soften under shear, whereas nanoparticle-reinforced films can be robust mechanically. We recommend that robust experimental protocols must therefore include at least one dynamic test at Reynolds numbers and shear rates representative of anticipated downhole flow, because these conditions provide a more realistic performance assessment for drilling operations.

5.6. Field monitoring of corrosion

Translating laboratory metrics to field decisions requires continuous monitoring tools that capture both short-term spikes

and long-term loss. Conventional weight-loss coupons remain the standard for average corrosion rate estimation, while electrical-resistance (ER) probes and linear polarization resistance (LPR) sensors provide real-time data under flowing mud conditions (Zehra et al., 2025). Recent advances have integrated electrochemical impedance spectroscopy (EIS) with downhole telemetry, permitting operators to adjust the inhibitor dosage and mud chemistry in real-time. Comparative studies reveal ER and LPR correlate well with weight loss when properly calibrated; however, instrument placement, fouling, and temperature compensation are routine sources of error (Martinelli-Orlando and Angst, 2022). These developments bridge laboratory evaluation and field implementation, ensuring that corrosion mitigation strategies remain effective under HPHT drilling environments.

The literature reviews show common weaknesses: (a) omission of HPHT aging, (b) absence of dynamic/shear tests, (c) failure to test multiple salinities and dissolved-gas conditions, and (d) testing on only one alloy (Martinelli-Orlando and Angst, 2022; Retnanto et al., 2024; Zehra et al., 2025). To raise confidence in laboratory screening and enable cross-study comparison, we recommend mandatory reporting of: (i) full mud recipe (solid, ionic composition, additives and concentrations), (ii) dissolved-gas content (O_2, CO_2 partial pressure), (iii) HPHT aging protocol (temperature, time, pressure), (iv) dynamic/shear test conditions (RCE rpm, flow-loop Re), and (v) alloy tested with coupon geometry. Studies lacking these details should be interpreted as preliminary mechanistic explorations rather than field-ready validation.

6. Advances in corrosion inhibitor technology

In recent years, advances in inhibitor technology have significantly enhanced performance, sustainability, and compatibility with drilling fluids. Emerging trends include smart and responsive inhibitors, nano-enhanced systems, and green, eco-friendly alternatives that meet stricter environmental regulations (Yahya et al., 2022).

6.1. Smart and responsive corrosion inhibitors

Smart corrosion inhibitors use microcapsules or polymer carriers that respond to triggers such as pH and temperature to release corrosion inhibitors in situ (Li et al., 2025). This targeted release minimizes continuous release into the fluid and reduces environmental load. Mechanistically, release in acidic microenvironments regenerates the inhibitor concentration at anodic sites where film breakdown or local acidification has occurred; the released molecules adsorb and rebuild the protective film (Li et al., 2025). Bench-scale studies in simplified electrolytes show impressive inhibition efficiency in controlled saline tests and lab flow conditions; however, only a few have been validated in full drilling-mud matrices and under HPHT conditions. The challenges include: (i) ensuring capsule integrity under high shear cycles during circulation, (ii) matching trigger thresholds to real downhole conditions, and (iii) confirming the carrier does not negatively affect mud rheology or filtration. We recommend that any smart inhibitor study in drilling contexts report (a) capsule survival after shearing/aging, (b) release profile under mud chemistry and HPHT, and (c) combined corrosion and mud compatibility testing (API rheology, LPLT/HPHT filtration).

Recent studies by Jin et al. (2025) demonstrated a microcapsule imidazoline core for pipe corrosion, exhibited excellent self-healing in pipeline simulants and some thermal stability data, but not tested in drilling mud matrices yet, which is an explicit gap. Cao et al. (2024) also showed that Solid Corrosion Inhibitor Capsule (SCICs) exhibited long-term release in coating with a corrosion efficiency of 80% towards N80 steel, but will require adaptation for mud dispersion and survivability under circulation.

6.2. Nanotechnology in corrosion inhibition

Nanomaterials can enhance corrosion protection in complex fluids by forming tighter, mixed inorganic-organic films, acting as reservoirs for inhibitor molecules, or altering local electrochemistry. Mechanistically, they can block pores in filter cakes and co-adsorb with organic inhibitors to yield composite films with increased resistance. However, in practical WBM formulations, the effective nanoparticle surface area is often far lower than in laboratory nanofluid tests due to aggregation and adsorption onto barite (Dejtaradon et al., 2019). A comprehensive review by Ikram et al. (2021) on eco-friendly nanomaterials for drilling fluids highlights benefits, but indicates knowledge gaps regarding corrosion testing in WBM, emphasizing that studies stop at rheology and filtration. Though these studies only report rheology or filtration, the work by Abdelsattar et al. (2020) is an important demonstration that corrosion testing can be carried out in true mud matrices, it tested metallo-cationic surfactant complexes in a prepared WBM and reported high inhibition efficiency as seen in Table 4, using classical electrochemistry and weight-loss tests in the mud matrix. Static corrosion studies do not account for high shear and circulation typical in drilling operations. Where dynamic drilling mud tests exist, inhibition efficiency decreases under simulated rotation (Abdelsattar et al., 2020). This indicates film stripping or mechanical removal of nanoparticle-linked films, hence, demands dynamic testing before claims of downhole efficacy. Gokapai et al. (2024) emphasized that nanoparticles may adsorb onto barite or clay platelets, changing both available nanoparticles for corrosion protection and the mud's filtration behavior. Ikram et al. (2021) also highlighted that many metallic nanoparticles, such as CuO and ZnO, raise ecotoxicology and disposal concerns, as full life-cycle assessments are rarely reported in laboratory studies.

6.3. Green corrosion inhibitors in drilling muds

Green corrosion inhibitors include plant extracts, seaweed extracts, biopolymers and natural deep eutectic solvents (NADES). They are attractive because they are low-cost, biodegradable, and derived from renewable sources (Sheydaei, 2024). However, while interest in green corrosion inhibitors continues to grow, experimental validation under real drilling-mud conditions has not kept pace. Most available studies show promising results in simple acidic or saline media such as HCl or NaCl, yet very few have tested these inhibitors within the complex, particle-rich systems that characterize actual drilling fluids containing bentonites, barite and other additives.

Plant extracts such as neem, henna, and alga polysaccharides show consistent inhibition in traditional electrochemical tests performed in simple acidic or saline environments. The reported inhibition efficiencies commonly exceed 60–90% depending on concentration, as seen in Table 3 and solvent extraction methods (Nadi et al., 2019; Valdez-Salas et al., 2021). These results indicate the extracts contain bioactive compounds, such as phenolics and carboxylates, that adsorb onto steel surfaces and reduce charge transfer. The majority of plant-alga studies test inhibitors in acids or brine solutions, not in complete drilling mud formulation. In reality, drilling fluids are complex, containing polymers that can significantly alter the behavior of the inhibitor. Within these particle-rich and high-salinity systems, the inhibitor may compete

with clays and weighting materials for adsorption sites (Ikram et al., 2021). Consequently, the corrosion efficiencies measured in acidic environments overestimate mud performance unless validated on the same mud recipe. Because many bioactive compounds degrade at elevated temperatures, and the HPHT tests commonly used in drilling fluids are rarely reported for plant-based inhibitors, thermal decomposition has become a concern. Furthermore, plant extracts vary depending on species, harvest time, solvent, and extraction procedure. This variability complicates scale-up and regulatory acceptance (Sheydaei, 2024).

NADES can act as green solvents and provide corrosion-mitigating properties through strong hydrogen-bond networks and surface adsorption. Their polar functional groups interact with metal surfaces, forming a blocking layer and modifying the local double-layer structure. Mechanistically, they adsorb at the metal-mud interface through H-bonding and electrostatic interactions. However, their viscosity and solubility in the continuous phase of drilling fluids control their distribution. Several drilling-mud studies demonstrate rheology, filtrate, and anti-shale benefits, and DES studies in acid media show strong surface adsorption. Rasool and Ahmad (2023) demonstrated that the NADES ($MgSO_4$:glycerine) added to API WBM formulations improved rheology and filtrate; corrosion metrics were not the core focus, although the paper discusses potential anti-corrosion mechanisms. This exemplifies the frequent shift toward rheology focus in NADES studies, an exploitable gap for corrosion researchers. Reported concerns from literature emphasize that NADES can be highly viscous and may partition poorly into the continuous phase of OBMs or be retained in cakes, which affects inhibitor availability at the metal surface (Rasool et al., 2023). Furthermore, thermal breakdown of NADES hydrogen-bond networks at HPHT may cause loss of function. Although NADES studies in acid media seem promising, key constraints for their application in drilling mud include thermal degradation, potential interactions with mud polymers, and the need to control viscosity. For deployment, we recommend testing NADES in the exact mud formulation intended for use, including rheological and filtration assessments at targeted HPHT conditions, as well as electrochemical and weight loss testing on representative steel alloys.

6.4. AI and machine learning in corrosion prediction

Artificial intelligence (AI) and Machine learning (ML) are emerging as transformative tools in predicting corrosion rates and screening novel corrosion inhibitors. Since conventional corrosion models are based on empirical correlations and mechanistic approaches, these methods struggle with complex, non-linear interactions inherent to corrosion processes. AI and ML offer data-driven methods that provide improved accuracy and cost efficiency by learning from experimental and field data (Haruna et al., 2024; Mythreyi et al., 2021). Data-driven modelling involves leveraging historical and real-time data to predict corrosion rates by learning patterns in various operational parameters. Fig. 18 presents the steps taken in this process.

The data set for corrosion often includes environmental variables, material properties, and operational conditions. After data collection, preprocessing techniques such as principal component analysis (PCA) and normalization are applied to reduce dimensionality, standardize corrosion data, and improve model performance (Ossai, 2019). Several algorithms of ML models are available, ranging from simple linear regression and support vector regression (SVR) to more complex approaches such as decision trees, ensemble methods, and neural networks (NN). Trisnapradika et al. (2024) used quantitative structure-property relationships (QSPR) to predict the corrosion inhibition efficiency of pyridazine corrosion inhibitors, they reported a significant improvement in predictive accuracy, with R^2 values reaching up to 0.97 and root mean square error (RMSE) values decreasing substantially. These findings suggest that incorporating environmental and process variables into ML models not only enhances prediction accuracy but also facilitates the identification of critical factors, such as surface modification and heat treatment, that influence corrosion behavior. Imran et al. (2023) employed the extreme gradient boosting (XGB) model to predict marine corrosion, where it delivered robust predictions when tuned with hyperparameter optimization. Hybrid models, which combine statistical techniques with AI methods, have demonstrated more robust predictive capabilities. In a recent study by Serrano et al. the hybrid approach showed improved accuracy in predicting corrosion degradation in complex marine systems (Serrano et al., 2024). To ensure model robustness, rigorous cross-validation and testing on independent datasets are crucial. Advanced machine learning techniques, including deep learning, are employed to address non-linear relationships and interactions between variables in corrosion datasets (Ruiz et al., 2024).

Over the years, the development of effective corrosion inhibitors has traditionally relied on trial-and-error experimentation. The advent of AI-assisted screening is revolutionizing this process through virtual screening and molecular modelling, optimization of the formulations, and integration with experimental results (Pham et al., 2024). Fig. 19 shows the procedures in AI-assisted screening.

Machine learning algorithms can screen inhibitors by predicting the performance potential of inhibitory molecules through analyzing large databases of chemical structures and known inhibition efficiencies. This will enable the rapid identification of promising candidates before laboratory synthesis and testing (Hughes et al., 2022). The study of Winkler (2017) showed that the integration of ML with throughput synthesis techniques has accelerated the discovery of benign organic corrosion inhibitors, allowing for rapid testing and validation. Integrating AI techniques with molecular dynamics provides a detailed insight into how inhibitors interact with metal surfaces at the atomic level. The results of these simulations enhance the understanding of adsorptive behavior and protective film formation, which are crucial for inhibitor performance (Imran et al., 2023). ML can be used to optimize the formulation of inhibitors using ensemble methods such as bagging and boosting. Comparative studies have revealed that non-linear ensemble models, such as bagging regressors, consistently deliver a superior performance compared to linear models when predicting corrosion inhibition efficiency (Wise et al., 2024). The application of ML to corrosion inhibition not only accelerates the screening process but also reduces the need for extensive laboratory experiments. A recent study by Wise et al. (2024) demonstrated that the bagging regressor model achieved an RMSE of 5.38 and an R^2 close to 0.72 in predicting the

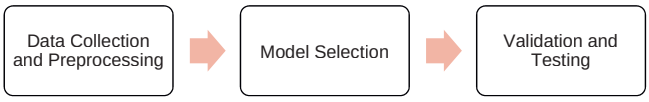


Fig. 18. Data-driven modelling steps.

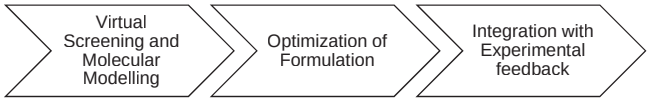


Fig. 19. AI-assisted screening processes.

efficiency of pyrimidine inhibitors. This approach highlights the potential for AI to serve as a cost-effective and rapid alternative to traditional experimental methods, enabling the discovery of new, environmentally friendly inhibitors. When AI predictions are combined with experimental validations, a feedback loop is created that refines both the inhibitor formulations and the predictive models. This integrated approach will significantly reduce the time and cost associated with developing new inhibitors, accelerating the translation from lab-scale discovery to industrial application (Imran et al., 2024).

7. Integrated Screening and Corrosion Inhibition Modelling (I-SCIM)

The development and optimization of corrosion inhibitors for drilling muds pose considerable challenges given their fragmented traditional approach, which often sees laboratory experiments, computational modelling, and field validation pursued independently of one another. Integrated Screening and Corrosion Inhibition Modelling (I-SCIM) has been proposed as part of this study. I-SCIM provides an advanced screening and modelling framework that will propel the discovery of inhibitors suited for very harsh operating conditions and promote environmental compliance. With its multi-phase approach, I-SCIM presents a paradigm shift in corrosion management, offering a scalable, data-driven strategy to meet the evolving demands of the oil and gas industry.

7.1. Need and significance of I-SCIM

Today, inhibitor candidates are often evaluated in isolated studies, where some focus on lab tests, others on modelling, and a few integrate both. This slows down innovation and leads to mismatches between academic findings and field performance. Geothermal wells, ultra-deep wells, CO_2 storage wells, and other modern wells impose multiple simultaneous stresses, such as HTHP and acidic gases, that single-method screens can't capture. Furthermore, environmental regulations require early screening for toxicity and biodegradability. The significance of the Integrated Screening and Corrosion Inhibition Modelling (I-SCIM) lies in its ability to unify all key aspects, including performance, stability, compatibility, sustainability, and cost into one streamlined pipeline, lowering the time-to-field by up to 50% and ensuring that top candidates are both effective and deployable. This framework combines high-throughput experimental techniques, advanced computational simulations, and machine learning analytics.

7.2. What will I-SCIM do?

I-SCIM will optimize inhibitor formulation by ensuring long-term stability, compatibility with various mud additives, and high corrosion inhibition efficiency. It will reduce time and cost by rapidly filtering promising candidates from a broad chemical space. Furthermore, it will enhance the understanding of structure-property relationships by integrating molecular-level insights with field performance data.

7.3. How does I-SCIM work?

I-SCIM proposes a multi-phase approach for selecting and developing corrosion inhibitors from a library of candidates. Candidate inhibitors undergo four phases of evaluation: high-throughput experimental screening, computational simulation and molecular modelling, machine learning-driven predictive modelling, and field validation and feedback integration. Fig. 20 shows a flowchart of the proposed I-SCIM.

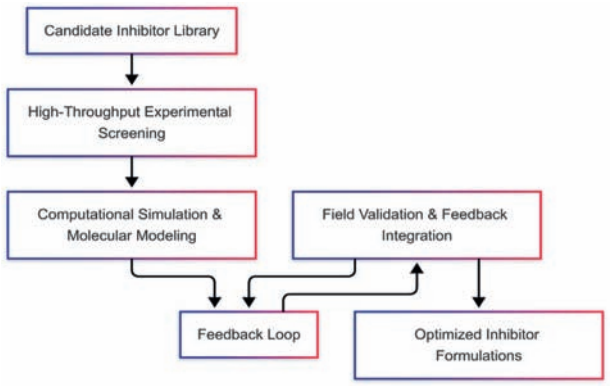


Fig. 20. Flowchart of the integrated screening and corrosion inhibition modelling (I-SCIM).

7.3.1. Phase I – high-throughput experimental screening

A laboratory setup is designed to screen a wide library of inhibitor formulations. This setup is designed to simulate downhole drilling conditions. Screening is carried out using (1) electrochemical tests (potentiodynamic polarization, electrochemical impedance spectroscopy) to measure corrosion efficiency, and gravimetric analysis, which includes rapid weight loss tests to determine the corrosion rate. (2) Compatibility and synergy test, where additive interactions and hybrid formulations are run in parallel with rheology and phase-separation checks. (3) Environmental simulation chambers to mimic HTHP and CO_2-rich conditions, ensuring that candidates are tested under realistic downhole environments.

The candidate inhibitors are screened using four critical screening criteria, namely: performance and stability, compatibility and synergy, environmental and regulatory compliance, and economics and operational feasibility. These criteria are designated values of 0–5, with 5 being the highest importance and 0 the least importance in screening the candidate inhibitors. Fig. 21 summarize the screening criteria.

The performance and stability metric criterion evaluates the corrosion inhibition efficiency (IE) using standard electrochemical techniques: potentiodynamic polarization, EIS, and the weight loss method. It also evaluates the long-term stability of the inhibitor under simulated downhole conditions, such as HTHP and CO_2-rich environments, to ensure sustained performance. The compatibility and synergistic interactions criterion evaluates the inhibitor's

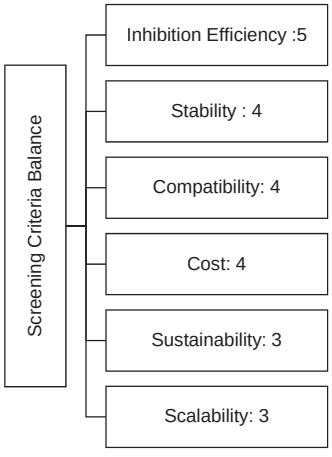


Fig. 21. Summary of the screening criteria for I-SCIM.

compatibility by ensuring that it does not negatively interact with other drilling mud components. Furthermore, identification of beneficial combinations that can yield improved protective films. The environmental and regulatory compliance criterion screens for inhibitors with low toxicity and high biodegradability, aligning with stringent environmental standards. Furthermore, it evaluates whether the formulation complies with international regulatory guidelines concerning hazardous substances and heavy metals. The economic and operational feasibility criterion evaluates the cost-effectiveness of the inhibitor, synthesis cost, dosing requirements, and overall viability. The feasibility of large-scale production and integration into existing drilling operations is appraised. This front-end application rapidly filters out low performers, ensuring only candidates meeting minimal thresholds across all four dimensions progress to Phase II.

7.3.2. Phase II – computational simulation and molecular modelling

This phase integrates molecular-level simulations to predict the behavior of the inhibitor. Density functional theory (DFT) and Molecular Dynamics (MD) are employed to calculate adsorption energies, film stability, and degradation pathways. Based on the calculated and predicted interactions at the metal surface, a virtual screening tool can be used to narrow down the most promising candidates from the library. The computational results provide crucial parameters that are fed into subsequent predictive models.

7.3.3. Phase III – machine learning-driven predictive modelling

This phase leverages advanced machine learning algorithms to synthesize the data obtained from Phases I and II. The purpose of this phase is to develop a robust predictive tool that can dynamically adjust inhibitor formulations in real time. This is achieved through data fusion and feature extraction, which entails integrating experimental and simulation data to identify key performance predictors. The development of models such as deep neural networks and extreme gradient boosting to forecast long-term inhibitor performance under variable conditions. And the optimization of algorithms, where the developed models are utilized to optimize formulation parameters for maximum efficiency and compatibility.

7.3.4. Phase IV – field validation and feedback integration

At this phase, pilot field tests are conducted to validate laboratory and simulation results. This phase ensures that the optimized inhibitor formulations are validated under actual drilling conditions, bridging the gap between laboratory research and field application. To achieve this, sensor networks would be employed to monitor corrosion rates and the continuous effectiveness of the inhibitor. Then, a feedback loop where field data are used to refine and retrain machine learning models, ensuring continuous improvement and adaptation to real-world conditions.

The Integrated Screening and Corrosion Inhibition Modelling (I-SCIM) explicitly addresses acceptability, adoption, appropriateness, feasibility, cost, and sustainability; hence, it ensures that both industry and academic stakeholders can adopt and effectively scale the framework, driving both scientific insight and real-world impact.

8. Challenges of corrosion inhibitors in drilling mud

In drilling operations, corrosion inhibitors are employed to protect the drilling equipment and enhance the performance of drilling mud under harsh conditions. In the past, many effective inhibitors have relied on heavy metals due to their excellent anti-corrosive properties. In more recent times, however, environmental concerns and toxicity have led to the restriction of heavy metal-based formulations worldwide (Askari et al., 2021). Considering this, the industrial trend is towards formulating environmentally compliant and friendly inhibitors.

8.1. Environmental and regulatory

Metals such as chromate, phosphate, molybdate, zinc, etc., have been used as corrosion inhibitors because they have the capability of forming a protective film over metal surfaces. Despite their efficacy, these compounds pose a significant risk not only to human beings but also to the environment. These toxic metals often accumulate in soil and water, resulting in harmful effects on aquatic life and bioaccumulation in food chains. Environmental burdens as these have led to a growing consensus that their use must be replaced, ensuring stricter global regulation (Ahmed et al., 2024). This regulatory pressure is driving the need for research into alternative inhibitor chemistries that do not rely on heavy metals while still providing robust corrosion protection (Askari et al., 2021). Drilling fluids are expected by regulatory bodies to meet certain sustainability criteria: low toxicity, biodegradability, and minimum environmental footprint. In recent years, sustainability has become a primary pillar in producing new corrosion inhibitors, ensuring that researchers focus on organic, bio-based, and waste-derived compounds instead of heavy-metal-based inhibitors. For example, new studies have demonstrated that waste materials and natural products can effectively be recycled as corrosion inhibitors in drilling fluids while decreasing their environmental footprint and production costs (Yahya et al., 2022). Such research not only supports regulatory compliance but also helps the industry transition to a circular economy.

8.2. Stability and long-term effectiveness

One major challenge experienced in the corrosion inhibitor formulation is the ability to maintain stability throughout the entire drilling operation. Downhole environments impose high temperature and pressure along with aggressive chemical attack on corrosion inhibitors. It is under these harsh conditions that the inhibitor molecules tend to degrade, or precipitate, out of the mud system, lessening their effectiveness over time. Studies have shown that even advanced inhibitor systems may suffer from reduced performance due to thermal degradation or oxidative processes (Yahya et al., 2022). Some new formulation strategies, such as encapsulation or the incorporation of synergistic additives, are being explored by researchers to enhance the durability of inhibitors (Safian et al., 2024). However, these strategies still require further validation in field trials.

Inhibitor additives should be compatible with other mud components to avoid adverse interactions that can change the properties of the mud, such as viscosity, gel strength, or fluid loss. Incompatibility of the inhibitor with other mud components is likely to lead to phase separation, reduced inhibition efficiency, or even chemical reactions that can produce undesirable byproducts. Therefore, optimizing inhibitor formulation requires a thorough understanding of how each component of the drilling mud interacts under varying conditions. Advanced characterization techniques and computational models are being increasingly utilized to predict and mitigate these interactions. The essence of compatibility studies is to ensure that inhibitors do not adversely affect mud performance parameters, such as fluid loss control and lubricity (Askari et al., 2021).

9. Conclusions and recommendations

In the oil and gas drilling industry, corrosion remains a critical challenge with immense economic, safety, and environmental implications. This paper presented a thorough discussion on the state-of-the-art corrosion inhibitors used in drilling muds. Inorganic inhibitors typically work through passivation, producing oxide layers to provide inhibition, while organic inhibitors work primarily through adsorption and pH changes to form a protective film. However, with the introduction of environmental regulations, the focus has shifted toward green alternatives, such as plant extracts, deep eutectic solvents (DES), and bio-based inhibitors, which offer biodegradability and reduced toxicity. Hybrid inhibitors and nanotechnology-based solutions have demonstrated clear synergistic benefits, particularly through enhanced barrier properties, improved thermal stability, and adaptive protection mechanisms. Advanced technology, such as smart coatings which respond to pH or temperature, alongside AI-driven predictive models, further reflects the rapid evolution of corrosion mitigation strategies towards more dynamic and intelligent systems. However, when these advanced approaches are evaluated against realistic drilling variables, including temperature, dissolved gases, salinity, metallurgy, and hydrodynamics, it becomes evident that static, ambient-condition testing remains fundamentally inadequate as a standalone screening approach.

Despite these technological advancements, significant challenges persist in translating laboratory success to field-scale implementation. Practical deployment is constrained by inhibitor degradation under high-temperature, high-pressure (HTHP) conditions, uncertainties in optimal dosing, and potential incompatibilities with other drilling fluid additives. Moreover, a substantial portion of existing studies continue to assess corrosion inhibition performance in isolation, without systematically evaluating the concurrent impact on drilling fluid rheology, filtration, and overall compliance with API specifications.

To enhance the efficiency of corrosion inhibitors, future research must prioritize interdisciplinary innovation to address these gaps. The integration of AI and machine learning into corrosion inhibition in drilling mud science will accelerate inhibitor discovery, optimize formulations, and enable real-time corrosion monitoring. Additionally, the scalable synthesis of smart self-healing coatings and responsive nanocontainers requires further investigation to balance performance and cost. Transitioning towards sustainable, high-efficiency corrosion inhibitors isn't just a mere technical necessity but a strategic imperative for the oil and gas industry. The drilling industry, by leveraging emerging technologies and prioritizing environmental stewardship, can achieve safer, more economical, and ecologically responsible drilling operations, ensuring long-term resilience in an era of evolving challenges.

Future research should focus on developing environmentally friendly inhibitors that are thermally stable and compatible with other drilling mud additives. Green inhibitors, derived from natural sources such as plant extracts and algae, are rich in bioactive compounds like polyphenols, tannins, and flavonoids. These inhibitors offer benefits such as high biodegradability, low toxicity, and renewable sourcing, all of which are critical under the increasingly strict environmental regulations imposed on drilling muds. While green inhibitors possess these benefits, they degrade under harsh drilling conditions; therefore, future research should focus on improving their thermal and chemical stability to withstand harsh drilling conditions such as HTHP and acidic conditions. Also, future research should prioritize HPHT-validated, dynamically tested, and formulation-aware inhibitor systems to ensure that laboratory-scale advancements translate into reliable, field-deployable corrosion control strategies in modern drilling operations. Furthermore, researchers should also focus on developing efficient and scalable methods to extract and purify bioactive compounds from plants and other natural resources.

Future research should extensively explore the use of machine learning and AI in optimizing inhibitor formulation. By analyzing large datasets from field operations and laboratory experiments, predictive models can be developed to optimize inhibitor compositions for maximum long-term performance and compatibility. These models can help identify synergistic interactions between inhibitors and other mud additives, accelerating the formulation development.

Future research should focus on integrating molecular-level studies with field-scale modeling. By combining density functional theory (DFT) calculations with machine learning algorithms, researchers can predict the performance of inhibitors across various environmental conditions. Such integrated approaches will aid in optimizing formulations before extensive field trials.

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CRediT authorship contribution statement

Precious Jumbo-Egwurugwu: Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Syahrir Ridha:** Supervision, Resources, Methodology, Conceptualization. **Muhammad Hammad Rasool:** Writing – review & editing, Visualization, Validation, Methodology. **Okorie Agwu Ekwe:** Writing – review & editing, Visualization, Validation, Supervision. **Shwetank Krishna:** Validation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abdelsattar, M., Badawi, A.E.M., Ibrahim, S., Wasfy, A.F., Tantawy, A.H., Dardir, M.M., 2020. Corrosion control of carbon steel in water-based mud by nanosized metallo-cationic surfactant complexes during drilling operations. ACS Omega 5, 30881–30897.

Acosta-Vega, L., Cifuentes, A., Ibanez, E., Galeano Garcia, P., 2025. Exploring natural deep eutectic solvents (NADES) for enhanced essential oil extraction: current insights and applications. Molecules 30.

Agarwal, A., Kumar, A., Sarkar, T.K., Saraswat, V., Yadav, M., Obot, I.B., Alamri, A.H., 2025. Amino acid-derived compounds as effective corrosion inhibitors for mild steel in hydrochloric acid: gravimetric, electrochemical and computational studies. Mater. Today Commun. 46, 112490.

Ahmad, Z., Khan, A.U., Farooq, R., Mastoi, N.R., Saif, T., 2015. Hydrophobicity — a green technique for enhancing corrosion resistance of alloys. In: Ahmad, Z. (Ed.), New Trends in Alloy Development, Characterization and Application. IntechOpen.

Ahmed, M.A., Amin, S., Mohamed, A.A., 2024. Current and emerging trends of inorganic, organic and eco-friendly corrosion inhibitors. RSC Adv. 14 (43), 31877–31920.

Akpan, E.D., Kumar Singh, A., Lgaz, H., Quadri, T.W., Kumar Shukla, S., Mangla, B., Dwivedi, A., Dagdag, O., Sheetal, Edem, Inyang, E., Ebenso, E.E., 2024. Coordination compounds as corrosion inhibitors of metals: a review. Coord. Chem. Rev. 499, 215503.

Al-Amiery, A.A., Isahak, W.N., Al-Azzawi, W.K., 2023. Corrosion inhibitors: natural and synthetic organic inhibitors. Lubricants 11 (4), 174.

Al-Hameedi, A.T., Alkinani, H.H., Dunn-Norman, S., Trevino, H.A., Al-Alwani, M.A., 2020. Conventional and eco-friendly hydraulic fracturing fluid additives: a review. In: SPE Hydraulic Fracturing Technology Conference and Exhibition.

Al-Rubaiey, N.A., Kadhim, F.S., Ati, A.A., 2017. Nano ferrites as corrosion inhibitors for carbon steel in local Iraqi bentonite mud. Eng. Technol. J. 35, 849–855.
Al-Shehri, D.A., 2019. Oil and gas wells: enhanced wellbore casing integrity management through corrosion rate prediction using an augmented intelligent approach. Sustainability 11 (3), 818.
Alanazi, N.M., Ulhaq, M.I., Al-Zahrani, T.Y., Saleem, Q., Leoni, M., Al-Mutahhar, F.M., Al-Shebil, R.A., Abeedi, T.M., 2023. Dual-purpose corrosion and kinetic hydrate inhibitors based on 3-acrylamidopropyl trimethyl ammonium copolymers. React. Funct. Polym. 190, 105626.
AlGaiar, M., Afolabi, J., 2024. Enhancing geothermal wells integrity: key considerations and challenges from drilling to production. In: SPE Symposium: Well Integrity Management.
Algburi, A.K.I., 2023. Evaluation of corrosion inhibition of carbon steel in crude oil by using different green corrosion inhibitors and various rotation speeds. J. Pet. Res. Stud. 13, 97–117.
Alkalbani, A.M., Chala, G.T., 2024. A comprehensive review of nanotechnology applications in oil and gas well drilling operations. Energies 17 (4), 798.
Allison, F., Nwanekezie, M., Osoka, E., 2019. Statistical modelling and optimization of the performance enhancement of Ubakala clay for use as drilling mud. International Journal of Scientific Research and Engineering Development 2 (3), 343–347.
Alrefaee, S.H., Rhee, K.Y., Verma, C., Quraishi, M.A., Ebenso, E.E., 2021. Challenges and advantages of using plant extract as inhibitors in modern corrosion inhibition systems: recent advancements. J. Mol. Liq. 321, 114666.
Amanullah, M., 2007. Screening and evaluation of some environment-friendly mud additives to use in water-based drilling muds. In: SPE Health, Safety, Security, Environment, and Social Responsibility Conference. North America.
Ansari, K.R., Singh, A., Quraishi, M.A., Saleh, T.A., 2022. Experimental methods of inhibitors assessment. In: Hussain, C.M., Verma, C., Aslam, J. (Eds.), Environmentally Sustainable Corrosion Inhibitors. Elsevier, pp. 97–123.
Arthur, D.E., Jonathan, A., Ameh, P.O., Anya, C., 2013. A review on the assessment of polymeric materials used as corrosion inhibitor of metals and alloys. Int. J. Ind. Chem. 4, 1–9.
Askari, M., Aliofkhazraei, M., Jafari, R., Hamghalam, P., Hajizadeh, A., 2021. Downhole corrosion inhibitors for oil and gas production – a review. Appl. Surf. Sci. Adv. 6, 100128.
Asrar, N., 2010. Corrosion control of drilling tools through chemical treatments: effectiveness and challenges. In: SPE International Conference on Oilfield Corrosion. Aberdeen, United Kingdom.
Badawi, A.K., Fahim, I.S., 2021. A critical review on green corrosion inhibitors based on plant extracts: advances and potential presence in the market. Int. J. Corros. Scale Inhib. 10.
Bai, M., Zhang, Z., Fu, X., 2016. A review on well integrity issues for CO_2 geological storage and enhanced gas recovery. Renew. Sustain. Energy Rev. 59, 920–926.
Ball, A.S., Stewart, R.J., Schliephake, K., 2012. A review of the current options for the treatment and safe disposal of drill cuttings. Waste Manag. Res. 30, 457–473.
Bassey, B.O., 2017. Asset Integrity and Profitability Enhancement at Three Process Facilities Through Corrosion Prevention, Control and Management. Coventry University, Coventry, United Kingdom, pp. 1–28.
Bertness, T.A., Chilingarian, G.V., Al-Bassam, M., 1989. Corrosion in drilling and producing operations. In: Chilingarian, G.V., Robertson, J.O., Kumar, S. (Eds.), Developments in Petroleum Science 19. Elsevier, pp. 283–317.
Bijapur, K., Molahalli, V., Shetty, A., Toghan, A., De Padova, P., Hegde, G., 2023. Recent trends and progress in corrosion inhibitors and electrochemical evaluation. Appl. Sci. 13.
Brondel, D., Edwards, R., Hayman, A., Hill, D., Mehta, S., Semerad, T., 1987. Corrosion in the oil industry. J. Pet. Technol. 39, 756–762.
Brondel, D., Edwards, R., Hayman, A., Hill, D., Mehta, S., Semerad, T., 1994. Corrosion in the oil industry. Oilfield Rev. 6 (2), 4–18.
Burke, C., Veil, J., 1995. Synthetic drilling muds: environmental gain deserves regulatory confirmation. In: SPE Health, Safety, Security, Environment, and Social Responsibility Conference – North America.
Cao, J., Wang, J., Xu, Y., Yuan, H., Yang, L., Yuan, H., 2024. A long-term effective solid capsule with matrix-type structure for the anticorrosion in oil and gas fields. J. Mater. Res. Technol. 29, 5022–5033.
Chen, H., Qin, Z., He, M., Liu, Y., Wu, Z., 2020. Application of electrochemical atomic force microscopy (EC-AFM) in the corrosion study of metallic materials. Materials 13 (3), 668.
Chen, L., Lu, D., Zhang, Y., 2022. Organic compounds as corrosion inhibitors for carbon steel in HCl solution: a comprehensive review. Materials 15, 2023.
Chilingar, G.V., Mourhatch, R., Al-Qahtan, G.D., 2008. The Fundamentals of Corrosion and Scaling for Petroleum and Environmental Engineers. Gulf Publishing Company.
Cirimello, P.G., Otegui, J.L., Carfi, G., Morris, W., 2017. Failure and integrity analysis of casings used for oil well drilling. Eng. Fail. Anal. 75, 1–14.
Committee, A.S.S.A.S.S., 2011. Drilling Fluids Processing Handbook. Elsevier.
Cron, C., Marsh, G., 1983. Overview of economic and engineering aspects of corrosion in oil and gas production. J. Pet. Technol. 35, 1033–1041.
Davydov, A., Alekseeva, E., Kolnyshenko, V., Strekalovskaya, D., Shvetsov, O., Devyaterikova, N., Laev, K., Alkhimenko, A., 2023. Corrosion resistance of 13Cr steels. Metals 13.
Dehghani, A., Bahlakeh, G., Ramezanzadeh, B., 2019. A detailed electrochemical/theoretical exploration of the aqueous Chinese gooseberry fruit shell extract as a green and cheap corrosion inhibitor for mild steel in acidic solution. J. Mol. Liq. 282, 366–384.
Dejtaradon, P., Hamidi, H., Chuks, M.H., Wilkinson, D., Rafati, R., 2019. Impact of ZnO and CuO nanoparticles on the rheological and filtration properties of water-based drilling fluid. Colloids Surf., A 570, 354–367.
Desimoni, E., Brunetti, B., 2015. X-ray photoelectron spectroscopic characterization of chemically modified electrodes used as chemical sensors and biosensors: a review. Chemosensors 3, 70–117.
Dey, S., Kiran, R., 2022. Bio-based inhibitors to mitigate internal corrosion in crude oil pipelines. Am. Soc. Civ. 73–78.
Dubey, S., 2018. Sustainable maintenance in drilling operations: new risks, changing standards and codes. In: SPE/IADC Middle East Drilling Technology Conference and Exhibition.
Eliaz, N., 2019. Corrosion of metallic biomaterials: a review. Materials 12.
Etsuyankpa, M.B., Hassan, I., Musa, S.T., Mathew, J.T., Shaba, E.Y., Andrew, A., Muhammad, A.I., Muhammad, K.T., Jibrin, N.A., Abubakar, M.K., Maurice, J., Hussaini, J., Mamman, A., 2024. Comprehensive review of recent advances in nanoparticle-based corrosion inhibition approaches. J. Appl. Sci. Environ. Manag. 28, 2269–2286.
Fateh, A., Aliofkhazraei, M., Rezvanian, A., 2020. Review of corrosive environments for copper and its corrosion inhibitors. Arab. J. Chem. 13, 481–544.
Fayomi, O., Akande, I., Odigie, S., 2019. Economic impact of corrosion in oil sectors and prevention: an overview. J. Phys., Conf. Ser. 1378 (2), 022037.
Galio, A.F., Dariva, C.G., 2014. Corrosion inhibitors – principles, mechanisms and applications. In: Aliofkhazraei, M. (Ed.), Developments in Corrosion Protection. IntechOpen.
Galvan-Martinez, R., Galvan-Martinez, R., Mendoza-Flores, J., Duran-Romero, R., Genesca, J., 2007. Effect of turbulent flow on the anodic and cathodic kinetics of API X52 steel corrosion in H_2S-containing solutions: a rotating cylinder electrode study. Mater. Corros. 58, 514–521.
Ghaderi, S., Haddadi, S.A., Davoodi, S., Arjmand, M., 2020. Application of sustainable saffron purple petals as an eco-friendly green additive for drilling fluids: a rheological, filtration, morphological, and corrosion inhibition study. J. Mol. Liq. 315, 113707.
Ghasemi, K., Akbari, A., Jahani, S., Kazemzadeh, Y., 2024. A critical review of life cycle assessment and environmental impact of the well drilling process. Can. J. Chem. Eng. 103 (6).
Ghehsareh, Z., Sayah, T., Moharramnejad, M., Rahimitabar, A., Ehsani, A., 2025. Green guardians: a comprehensive review of environmentally friendly corrosion inhibitors from plant extract to ionic-liquids in industrial applications. Prog. Org. Coating 201.
Gokapai, V., Pothana, P., Ling, K., 2024. Nanoparticles in drilling fluids: a review of types, mechanisms, applications, and future prospects. Eng 5, 2462–2495.
González-Parra, J.R., Di Turo, F., 2024. The use of plant extracts as sustainable corrosion inhibitors for cultural heritage alloys: a mini-review. Sustainability 16.
Gowri, S., Umasankareswari, T., Joseph Rathish, R., Santhana Prabha, S., Rajendran, S., Al-Hashem, A., Singh, G., Verma, C., 2023. Atomic force microscopy technique for corrosion measurement. In: Aslam, J., Verma, C., Hussain, C.M. (Eds.), Electrochemical and Analytical Techniques for Sustainable Corrosion Monitoring. Elsevier, pp. 121–140.
Guangyu, Z., 2013. Exploration on Optimizing Maintenance Management by Using Condition Monitoring on Drilling Platforms. COSL University of Stavanger, Norway.
Hachem, D., Nguyen, D., Bonnecaze, R., Nguyen, Q., 2025. AFM characterization of corrosion inhibitors and nanoparticle films. ACS Appl. Eng. Mater. 3 (3).
Hamza, S.F., Abdelsalam, F.H., El-Wahab, H.A., Esmail, M.M., 2026. Polyethylene glycol-derived symmetric and asymmetric cationic gemini surfactants: synthesis, surface behavior and corrosion inhibition on carbon steel in acidic media. J. Mol. Struct. 1353, 144722.
Haruna, K., Abba, S.I., Usman, J., Usman, A.G., Musa, A., Saleh, T.A., Aljundi, I.H., 2024. Machine learning insight into inhibition efficiency modelling based on modified graphene oxide of diaminohexane (DAH-GO) and diaminooctane (DAO-GO). Carbon Trends 16, 100373.
Hernández García, S., Espinoza Vázquez, A., Palacios-Grijalva, L.N., Martínez Jiménez, A., Rodríguez Gómez, F.J., Gómez Vargas, Ó.A., Miralrio, A., Castro, M., Orozco Cruz, R., 2025. Effect of the use of some rare earth compounds as corrosion inhibitors for API 5L X70 steel in saline medium. Metals 15.
Hossain, M.E., Al-Majed, A.A., 2015. Fundamentals of Sustainable Drilling Engineering. Scrivener Publishing.
Hughes, A.E., Winkler, D.A., Carr, J., Lee, P.D., Yang, Y.S., Laleh, M., Tan, M.Y., 2022. Corrosion inhibition, inhibitor environments, and the role of machine learning. Corros. Mater. Degrad. 3, 672–693.
Ibukun, M., Elyan, E., Amish, M., Njuguna, J., Oluyemi, G.F., 2024. A review of well life cycle integrity challenges in the oil and gas industry and its implications for sustained casing pressure (SCP). Energies 17, 5562.
Ikram, R., Mohamed Jan, B., Sidek, A., Kenanakis, G., 2021. Utilization of eco-friendly waste generated nanomaterials in water-based drilling fluids: state of the art review. Materials 14.
Imran, M.M., Jamaludin, S., Ayob, A.F., Ali, A.A., Ahmad, S.Z., Akhbar, M.F., Suhrab, M.I., Zainal, N., Norzeli, S.M., Mohamed, S.B., 2023. Application of artificial intelligence in marine corrosion prediction and detection. J. Mar. Sci. Eng. 11.
Imran, M.M., Jamaludin, S., Faisal, A., Ayob, M., Chowdhury, R., Khan, M., Hasan, I., Ullah, A., Rezaul, M., 2024. Application of artificial intelligence in corrosion research, part II: corrosion of steel. Chin. Sci. Bull. 69 (8), 2721–2735.
Islam, M.R., Hossain, M.E., 2020. Drilling Engineering: towards Achieving Total Sustainability. Gulf Professional Publishing.

Ismail, A.R., Mohd, N.M.N.A., Basir, N.F., Oseh, J.O., Ismail, I., Blkoor, S.O., 2020. Improvement of rheological and filtration characteristics of water-based drilling fluids using naturally derived henna leaf and hibiscus leaf extracts. J. Pet. Explor. Prod. Technol. 10, 3541–3556.
Jaf, P.T., Ali, J.A., Razzaq, A.A.A., 2023. Drilling pipe corrosion reduction using natural, biodegradable, and environmentally friendly additive to the drilling fluid. ARO Sci. J. Koya Univ. 11, 138–142.
Jaramillo Clerque, K.G., 2022. Comprehensive Analysis of Corrosion in Offshore Systems in Gas Condensate Production. Universidad de Investigación de Tecnología Experimental Yachay, Ecuador.
Jiashen, Z., Jingmao, Z., 1993. Control of corrosion by inhibitors in drilling muds containing high concentration of H_2S. Corrosion 49, 170–174.
Jin, X., Yan, X., Wang, L., Deng, S., Cao, L., Ma, J., 2025. A novel self-healing anti-corrosive inhibitor for pipeline corrosion protection in geothermal well systems. ACS Omega 10, 12088–12096.
Kadhim, A., Al-Amiery, A.A., Alazawi, R., Ghezi, M.K.S.A., Abass, R.H., 2021. Corrosion inhibitors: a review. Int. J. Corros. Scale Inhib. 10.
Kadhim, M.G., Ali, M.T., 2017. A critical review on corrosion and its prevention in the oil field equipment. J. Pet. Res. Stud. 7 (2), 162–189.
Kartal, A., Yıldız, R., Döner, A., Baran, M.F., 2025. Thorough examination of *Polygonum aviculare* L. plant leaf extract as a green corrosion inhibitor for mild steel in 1 M HCl: synthesis, characterization, observations from surface analysis, experimental and DFT studies. Inorg. Chem. Commun. 176, 114241.
Karthik, G., Sundaravadivelu, M., 2016. Studies on the inhibition of mild steel corrosion in hydrochloric acid solution by atenolol drug. Egypt. J. Pet. 25, 183–191.
Khan, A., Fayyaz, O., Shakoor, R.A., Mansoor, B., 2022. Recent trends in applications of X-ray photoelectron spectroscopy (XPS) technique in coatings for corrosion protection. In: Toor, I.U. (Ed.), Recent Developments in Analytical Techniques for Corrosion Research. Springer International Publishing, pp. 167–186.
Khan, M.A.A., Irfan, O.M., Djavanroodi, F., Asad, M., 2022. Development of sustainable inhibitors for corrosion control. Sustainability 14, 9502.
Khodja, M., Khodja-Saber, C., Canselier, J.P., Cohaut, N., Bergaya, F., 2010. Drilling fluid technology: performances and environmental considerations. In: Fuerstner, I. (Ed.), Products and Services: from R&D to Final Solutions. IntechOpen, pp. 227–256.
Khormali, A., Ahmadi, S., Kazemzadeh, Y., Karami, A., 2025. Evaluating the efficacy of binary benzimidazole derivatives as corrosion inhibitors for carbon steel using multi-modal analysis and optimization techniques. Results Eng. 26, 104671.
Km, S., Praveen, B.M., Devendra, B.K., 2024. A review on corrosion inhibitors: types, mechanisms, electrochemical analysis, corrosion rate and efficiency of corrosion inhibitors on mild steel in an acidic environment. Results Surf. Interfaces 16, 100258.
Koch, G., 2017. Cost of corrosion. In: El-Sherik, A.M. (Ed.), Trends in Oil and Gas Corrosion Research and Technologies. Woodhead Publishing, pp. 3–30.
Labouche, D., Parrott, B., 2013. Contribution of nanomaterials to high corrosion protection. Trans. IMF 88, 8–10.
Li, D., Zhang, Z., Sukhbat, B., Wang, X., Zhang, X., Yan, J., Zhang, J., Zhang, Q., Li, Y., Wang, H., Yan, Y., 2025. Smart inhibitor systems towards anti-corrosion: design and applications. RSC Appl. Polym. 3, 532–548.
Li, H.-X., Li, D.-P., Zhang, L., Wang, Y.-W., Wang, X.-Y., Lu, M.-X., 2019. Passivity breakdown of 13Cr stainless steel under high chloride and CO_2 environment. Int. J. Min. Met. Mater. 26, 329–336.
Lindsay, R., Thomas, A., 2022. Introducing X-ray photoelectron spectroscopy for corrosion studies: a tool for elucidating interfacial composition and chemistry. In: Amjad, Z., Demadis, K.D. (Eds.), Water-Formed Deposits. Elsevier, pp. 723–745.
Loto, R.T., Busari, A., 2020. Inhibition effect of rosemary oil on mild steel corrosion in a water-based petrochemical drilling fluid. IOP Conf. Ser. Mater. Sci. Eng. 770, 012046.
Loto, R.T., Loto, C.A., Popoola, A., 2012. Corrosion inhibition of thiourea and thiadiazole derivatives: a review. J. Mater. Environ. Sci. 3, 885–894.
Lyons, W., 2009. Working Guide to Drilling Equipment and Operations. Gulf Professional Publishing.
Ma, I.W., Ammar, S., Kumar, S.S., Ramesh, K., Ramesh, S., 2022. A concise review on corrosion inhibitors: types, mechanisms and electrochemical evaluation studies. J. Coating Technol. Res. 19, 1–28.
Mainier, F.B., Figueiredo, A.A.M., Freitas, A.E.R.d., Junior, A.A.M.d.A., 2016. The use of sodium silicate as a corrosion inhibitor in a saline drilling fluid: a nonaggressive option to the environment. J. Environ. 7, 2025–2035.
Martinelli-Orlando, F., Angst, U., 2022. Monitoring corrosion rates with ER-probes – a critical assessment based on experiments and numerical modelling. Corrosion Eng. Sci. Technol. 57, 254–268.
Minagalavar, R.L., Rajappa, S.K., Rathod, M.R., Sajjan, A.M., 2023. Investigation of corrosion inhibition performance of expired fluconazole drug on mild steel in 0.5 M H_2SO_4 medium. J. Mol. Liq. 391, 123291.
Miralrio, A., Espinoza Vázquez, A., 2020. Plant extracts as green corrosion inhibitors for different metal surfaces and corrosive media: a review. Processes 8.
Mubarak, G., Verma, C., Barsoum, I., Alfantazi, A., Rhee, K.Y., 2023. Internal corrosion in oil and gas wells during casings and tubing: challenges and opportunities of corrosion inhibitors. J. Taiwan Inst. Chem. Eng. 150, 105027.
Mythreyi, O.V., Srinivaas, M.R., Amit Kumar, T., Jayaganthan, R., 2021. Machine-learning-based prediction of corrosion behavior in additively manufactured Inconel 718. Data 6 (8), 80.
Nadi, I., Belattmania, Z., Sabour, B., Reani, A., Sahibed-Dine, A., Jama, C., Bentiss, F., 2019. Sargassum muticum extract based on alginate biopolymer as a new efficient biological corrosion inhibitor for carbon steel in hydrochloric acid pickling environment: gravimetric, electrochemical and surface studies. Int. J. Biol. Macromol. 141, 137–149.
Negm, N.A., Tawfik, S.M., Badr, E.A., Abdou, M.I., Ghuiba, F.M., 2015. Evaluation of some nonionic surfactants derived from vanillin as corrosion inhibitors for carbon steel during drilling processes. J. Surfactants Deterg. 18, 413–420.
Obot, I.B., Sorour, A.A., Malede, Y.C., Chen, T., Wang, Q., Aljeaban, N., 2023. A review study on the challenges and progress of corrosion inhibitor testing under extreme conditions in the oil and gas industries. Geoenergy Sci. Eng. 226, 211762.
Odeyemi, O.O., Alaba, P.A., 2024. Microbiologically influenced corrosion in oil fields: mechanisms, detection, and mitigation strategies. In: Ou, J.F. (Ed.), Corrosion Engineering-Recent Breakthroughs and Innovative Solutions. IntechOpen.
Odeyemi, O.O., Alaba, P.A., 2025. Efficient and reliable corrosion control for subsea assets: challenges in the design and testing of corrosion probes in aggressive marine environments. Corrosion Rev. 43, 79–126.
Oni, O., Fadairo, A., Ojo, I., Foerster, I., 2025. Exploring limonite pigment as a sustainable corrosion inhibitor for drill pipe protection in high-pressure, high-temperature environments. In: 59th U.S. Rock Mechanics/Geomechanics Symposium.
Osokogwu, O., 2012. Evaluation of corrosion inhibitors effectiveness in oilfield production operations. Int. J. Sci. Technol. Res. 1, 19–23.
Ossai, C.I., 2019. A data-driven machine learning approach for corrosion risk assessment—a comparative study. Big Data Cogn. Comput. 3.
Palimi, M.J., Tang, Y., Alvarez, V., Kuru, E., Li, D.Y., 2022. Green corrosion inhibitors for drilling operation: new derivatives of fatty acid-based inhibitors in drilling fluids for 1018 carbon steel in CO_2-saturated KCl environments. Mater. Chem. Phys. 288, 126406.
Palimi, M.J., Tang, Y.Q., Mousavi, S.E., Chen, W., Alvarez, V., Kuru, E., Li, D.Y., 2023. Tribo-corrosion behavior of C-steel in water-based emulsion drilling fluids containing green corrosion inhibitors: experimental and computational studies. Tribol. Int. 187, 108728.
Papavinasam, S., 2013. Corrosion Control in the Oil and Gas Industry. Elsevier.
Pavithra, M.K., Venkatesha, T.V., Punith Kumar, M.K., Tondan, H.C., 2012. Inhibition of mild steel corrosion by rabeprazole sulfide. Corros. Sci. 60, 104–111.
Pham, T.H., Le, P.K., Son, D.N., 2024. A data-driven QSPR model for screening organic corrosion inhibitors for carbon steel using machine learning techniques. RSC Adv. 14, 11157–11168.
Pial, M.B., Islam, M.A., 2025. The effectiveness of natural corrosion inhibitors in corrosive media. Results Surf. Interfaces 19, 100516.
Picchio, M.L., Minudri, D., Mantione, D., Criado-Gonzalez, M., Guzman-Gonzalez, G., Schmarsow, R., Muller, A.J., Tome, L.C., Minari, R.J., Mecerreyes, D., 2022. Natural deep eutectic solvents based on choline chloride and phenolic compounds as efficient bioadhesives and corrosion protectors. ACS Sustain. Chem. Eng. 10, 8135–8142.
Popoola, L.T., Grema, A.S., Latinwo, G.K., Gutti, B., Balogun, A.S., 2013. Corrosion problems during oil and gas production and its mitigation. Int. J. Ind. Chem. 4, 1–15.
Prasad, A.R., Kunyankandy, A., Joseph, A., 2020. Corrosion inhibition in oil and gas industry: economic considerations. In: Saji, V.S., Umoren, S. (Eds.), Corrosion Inhibitors in the Oil and Gas Industry. Wiley-VCH Verlag GmbH & Co. KGaA, pp. 135–150.
Prasanna, B.M., Praveen, B.M., Hebbar, N., Venkatesha, T.V., Tandon, H.C., 2016. Inhibition study of mild steel corrosion in 1 M hydrochloric acid solution by 2-chloro 3-formyl quinoline. Int. J. Ind. Chem. 7, 9–19.
Raja, P.B., Ismail, M., Ghoreishiamiri, S., Mirza, J., Ismail, M.C., Kakooei, S., Rahim, A.A., 2016. Reviews on corrosion inhibitors: a short view. Chem. Eng. Commun. 203, 1145–1156.
Rani, B.E.A., Basu, B.B.J., 2012. Green inhibitors for corrosion protection of metals and alloys: an overview. Int. J. Corros. 2012, 380217.
Rasool, M.H., Ahmad, M., 2023. Epsom salt-based natural deep eutectic solvent as a drilling fluid additive: a game-changer for shale swelling inhibition. Molecules 28.
Rasool, M.H., Ahmad, M., Siddiqui, N.A., Junejo, A.Z., 2023. Eco-friendly drilling fluid: calcium chloride-based natural deep eutectic solvent (NADES) as an all-rounder additive. Energies 16.
Răuță, D.-I., Matei, E., Avramescu, S.-M., 2025. Recent development of corrosion inhibitors: types, mechanisms, electrochemical behavior, efficiency, and environmental impact. Technologies 13.
Ravi, M., Jennifer G, A., Varathan, E., Selvi, J.,A., 2025. Exploring the dual aspects of Sapindus mukorossi pod as a novel sustainable biosurfactant-based corrosion inhibitor for carbon steel in saline environment: an experimental and theoretical insights. J. Mol. Struct. 1337, 142065.
Raviprabha, K., Bhat, R.S., 2023. Corrosion inhibition of mild steel in 0.5 M HCl by substituted 1,3,4-oxadiazole. Egypt. J. Pet. 32, 1–10.
Retnanto, A., Yrac, R., Shaikh, A., Alagha, R., Alsulaiti, F., Chagouri, T., 2024. Experimental evaluation of corrosion inhibitors for completion fluids in the petroleum production systems. J. Pet. Explor. Prod. Technol. 14, 331–342.
Ruiz, D., Casas, A., Escobar, C.A., Perez, A., Gonzalez, V., 2024. Advanced machine learning techniques for corrosion rate estimation and prediction in industrial cooling water pipelines. Sensors 24.

Safian, M.T.-u., Pandian, B.R., Mohamad Ibrahim, M.N., 2024. The importance and evolution of corrosion inhibitors in the drilling fluid for the offshore drilling industry. Corrosion Rev. 42, 399–433.
Serrano, A.A.A., Miralrio, A., Beltran-Perez, C., 2024. Models for predicting corrosion inhibition efficiency of common drugs on steel surfaces: a rationalized comparison among methodologies. Appl. Surf. Sci. Adv. 22, 100621.
Shanbhag, A.V., Venkatesha, T.V., Prabhu, R.A., Praveen, B.M., 2011. Inhibition effects of acetyl coumarines and thiazole derivatives on corrosion of zinc in acidic medium. Bull. Mater. Sci. 34, 571–576.
Shang, Z., Zhu, J., 2021. Overview on plant extracts as green corrosion inhibitors in the oil and gas fields. J. Mater. Res. Technol. 15, 5078–5094.
Sharma, S., Richika, G., Abhinay, T., Kumar, A., 2023. Electrochemical characterization and surface morphology techniques for corrosion inhibition—a review. Chem. Eng. Commun. 210, 412–447.
Sheetal, Batra, R., Singh, A.K., Singh, M., Thakur, S., Pani, B., Kaya, S., 2023. Advancement of corrosion inhibitor system through N-heterocyclic compounds: a review. Corrosion Eng. Sci. Technol. 58, 73–101.
Sheydaei, M., 2024. The use of plant extracts as green corrosion inhibitors: a review. Surfaces 7, 380–403.
Shinato, K.W., Huang, F., Jin, Y., 2020. Principle and application of atomic force microscopy (AFM) for nanoscale investigation of metal corrosion. Corrosion Rev. 38, 423–432.
Singh, A.K., Singh, A.K., 2020. Industrial cases of microbial induced corrosion. In: Singh, A.K. (Ed.), Microbially Induced Corrosion and its Mitigation. Springer, pp. 81–106.
Solovyeva, V.A., Almuhammadi, K.H., Badeghaish, W.O., 2023. Current downhole corrosion control solutions and trends in the oil and gas industry: a review. Materials 16.
Tamalmani, K., Husin, H., 2020. Review on corrosion inhibitors for oil and gas corrosion issues. Appl. Sci. 10.
Trabanelli, G., 2020. Corrosion inhibitors. In: Corrosion Mechanisms. CRC Press, pp. 119–163.
Trisnapradika, G.A., Akrom, M., Rustad, S., Dipojono, H.K., Maezono, R., Kasai, H., 2024. A machine learning approach for forecasting the efficacy of pyridazine corrosion inhibitors. Theor. Chem. Acc. 144, 8.
Valdez-Salas, B., Vazquez-Delgado, R., Salvador-Carlos, J., Beltran-Partida, E., Salinas-Martinez, R., Cheng, N., Curiel-Alvarez, M., 2021. *Azadirachta indica* leaf extract as green corrosion inhibitor for reinforced concrete structures: corrosion effectiveness against commercial corrosion inhibitors and concrete integrity. Materials 14.
Wang, L., Wang, H., Seyeux, A., Zanna, S., Pailleret, A., Nesic, S., Marcus, P., 2023. Adsorption mechanism of quaternary ammonium corrosion inhibitor on carbon steel surface using ToF-SIMS and XPS. Corros. Sci. 213, 110952.
Wang, Z., Yin, D., Luo, Y., Liang, H., Yang, L., Lu, H., 2013. Corrosion and its inhibition in water-based drilling fluid used in onshore oilfield. Nat. Resour. 4, 456–459.
Winkler, D.A., 2017. Predicting the performance of organic corrosion inhibitors. Metals 7.
Wise, H., Wahyu Aji Eko, P., Muhamad, A., Totok, S., Noor Ageng, S., Achmad Wahid, K., Novianto Nur, H., Supriadi, R., 2024. Prediction of corrosion inhibition efficiency based on machine learning for pyrimidine compounds: a comparative study of linear and non-linear algorithms. KnE Eng. 6.
Xionghu, Z., Egwu, S.B., Jingen, D., Liujie, M., 2021. Application of benzotriazole corrosion inhibitor in synthetic-based drilling fluid and its overall impact in improving drilling fluid functionality. In: SPE International Oilfield Corrosion Conference and Exhibition.
Yahya, S., Kee, K.E., Puad, M.J.M., Ismail, M.C., 2022. Evaluation on steel corrosion in water-based drilling fluids: inhibitors and scale involvement. J. Pet. Sci. Eng. 211, 110127.
Yalman, E., Federer-Kovacs, G., Depci, T., Khalaf, H.A., Aylikci, V., Aydin, M.G., 2022. Development of novel inhibitive water-based drilling muds for oil and gas field applications. J. Pet. Sci. Eng. 210.
Yang, H.-M., 2021. Role of organic and eco-friendly inhibitors on the corrosion mitigation of steel in acidic environments—a state-of-art review. Molecules 26, 3473.
Yasakau, K., 2020. Application of AFM-based techniques in studies of corrosion and corrosion inhibition of metallic alloys. Corros. Mater. Degrad. 1, 345–372.
Yousuf, N., Olayiwola, O., Guo, B., Liu, N., 2021. A comprehensive review on the loss of wellbore integrity due to cement failure and available remedial methods. J. Pet. Sci. Eng. 207, 109123.
Zehra, S., Mobin, M., Ahmad, R., 2025. Corrosion monitoring and inspection techniques in industrial environments. In: Zehra, S., Mobin, M., Ahmad, R. (Eds.), Industrial Corrosion: Fundamentals, Failure, Analysis and Prevention. Scrivener Publishing LLC, pp. 297–320.
Zhang, J., 2019. Study on corrosion status and control strategies in energy field in China. In: Hou, B. (Ed.), The Cost of Corrosion in China. Springer Singapore, pp. 251–554.
Zhang, Q., Shi, G., Zhang, G., 2025. In-depth insight into the synergistic inhibition mechanism of *Centella asiatica* extract and KI on the corrosion of carbon steel in acidic medium. Ind. Crops Prod. 234, 121643.
Zhang, Z., Feng, X., 2025. Synthesis and evaluation of new type plant extraction corrosion inhibitor. Geoenergy Sci. Eng. 245, 213495.
Zhao, X.D., Yang, J., Fan, X.Q., 2011. Review on research and progress of corrosion inhibitors. Appl. Mech. Mater. 44–47, 4063–4066.
Zheng, Y., 2020. Tribological Studies of Water-based Mud and self-welding Behaviour. Texas A&M University, United States (Ph.D. thesis).
Zhou, X., Dong, Q., Wei, D., Bai, J., Xue, F., Zhang, B., Ba, Z., Wang, Z., 2022. Smart corrosion inhibitors for controlled release: a review. Corrosion Eng. Sci. Technol. 58, 190–204.
Zhu, Y., Free, M.L., Woollam, R., Durnie, W., 2017. A review of surfactants as corrosion inhibitors and associated modeling. Prog. Mater. Sci. 90, 159–223.
Zhuang, W., Wang, X., Zhu, W., Zhang, Y., Sun, D., Zhang, R., Wu, C., 2021. Imidazoline gemini surfactants as corrosion inhibitors for carbon steel X70 in NaCl solution. ACS Omega 6, 5653–5660.