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IONIC LIQUIDS AS A CORROSION INHIBITOR

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ABSTRACT

Room-temperature ionic liquids (RTILs) are innovative salts characterized by low volatility, high thermal stability, and strong surface activity, making them highly effective corrosion inhibitors. Imidazolium-, ammonium-, and Brönsted acid–based RTILs provide excellent protection for metals like mild and carbon steel through mixed-type inhibition mechanisms and Langmuir-type adsorption. Their efficiency is influenced by factors such as alkyl chain length, type of anion, concentration, and operating temperature. At suitable concentrations, RTILs form dense protective layers that limit the penetration of corrosive species. Recent developments include smart inhibitor systems using chitosan microspheres and polymeric ionic liquids for controlled release and enhanced protection. Compared to conventional inhibitors, RTILs offer superior environmental compatibility, tunability, and thermal resistance. Their anticorrosive behavior is commonly analyzed by electrochemical impedance spectroscopy and potentiodynamic polarization. These liquids are emerging as sustainable and efficient solutions for corrosion mitigation in challenging environments like acidic media and CO_2 capture systems.

1. Introduction to Ionic Liquids and Their Role in Corrosion Inhibition

Room-temperature ionic liquids (RTILs) are salts that remain in the liquid state at ambient temperatures and are composed of organic cations paired with various anions. Owing to their distinctive characteristics and broad applicability, RTILs have garnered considerable interest, especially for their potential to act as corrosion inhibitors (1).

Research has shown that RTILs can effectively tackle corrosion problems in industrial environments, particularly in systems designed for CO_2 capture. Notably, imidazolium-based RTILs with ethyl groups have been examined for their corrosion-inhibiting performance in aqueous monoethanolamine solutions. Among those evaluated, [emim][acetate] emerged as the most effective in reducing corrosion within alkanolamine-based CO_2 capture processes (1). This underscores the value of RTILs as viable corrosion inhibitors in industrial contexts.

Beyond corrosion inhibition, RTILs are also employed in electrodeposition applications. For instance, RTILs derived from aluminium trichloride and benzyltrimethyl ammonium chloride enable the deposition of aluminium and aluminium/platinum alloys. These specific ionic liquids present several benefits, including reduced sensitivity to moisture, simpler purification methods,

and greater cost efficiency when compared to earlier solutions (2). This multifaceted utility of RTILs underlines their importance in materials science and engineering.

RTILs represent a promising class of corrosion inhibitors, especially for use in industrial operations like CO_2 capture. Their distinct characteristics—such as low volatility and high thermal stability—position them as strong contenders to replace traditional corrosion inhibitors. As studies in this area progress, RTILs are expected to assume a more significant role in overcoming corrosion challenges across a wide range of industries.

2. Synthesis and characterization of ionic liquids for corrosion inhibition

- Imidazolium-based ionic liquids

Imidazolium-based ionic liquids (ILs) have been widely researched as corrosion inhibitors for metals like mild steel and carbon steel, especially in acidic environments. These ILs are synthesized by combining imidazolium cations featuring various alkyl chain lengths with different anions (3)(4). Their properties are typically assessed through a combination of physicochemical and spectral analyses, along with computational studies using techniques such as B3LYP to evaluate optimized molecular structures, HOMO-LUMO distributions, and quantum chemical descriptors (4).

The inhibition performance of imidazolium-based ILs is notably affected by parameters such as the length of the alkyl chain, the nature of the anion, and the IL concentration. For example, one study reported the inhibition efficiency in the order: [PDMIM][NTf_2] > [HMIM][NTf_2] > [BMIM][NTf_2] > [PMIM][NTf_2], suggesting that longer chains and additional methyl groups on the imidazolium ring improve performance (3). Another investigation supported this trend, finding that longer alkyl chains enhanced the inhibitory effect of the ILs studied (5).

In summary, the synthesis and evaluation of imidazolium-based ILs for corrosion inhibition require strategic selection of both cation and anion components. These ILs typically demonstrate mixed-type inhibition, with their performance improving as concentration increases (5)(6). Their adsorption behavior on metal surfaces often aligns with the Langmuir adsorption isotherm, and they function primarily by forming protective layers on the substrate (7)(4). Innovative developments such as polymer-based ILs or ILs integrated into advanced delivery systems like chitosan microspheres offer promising pathways for advancing corrosion resistance (8).

- Ammonium-based ionic liquids

Ammonium-based ionic liquids (ILs) have been developed and examined in numerous studies for their effectiveness as corrosion inhibitors. In one such investigation, Cornejo Robles (9) synthesized 15 ILs derived from quaternary ammonium and carboxylate ions and tested them on API X52 steel in 0.5 M HCl. The inhibition efficiency (IE) varied based on the specific chemical structures of the anions and cations, with ILs such as [$THDA^+$][−AA], [$THDA^+$][−AI], and [$THDA^+$][−AD] achieving IE values between 56% and 84% (9).

In a related study, Olivares-Xometl et al. (2017) reported the synthesis of four novel halide-free ammonium-based ILs, which displayed inhibition efficiencies ranging from 51% to 89% when applied to API 5L X60 steel in 1 M sulfuric acid. Both investigations concluded that the ILs functioned as mixed-type inhibitors and adhered to the Langmuir adsorption isotherm model (10)(9).

Further exploration by Gabler et al. (11) focused on two ammonium-based ILs with potential lubricating properties, particularly assessing their corrosion resistance. The study evaluated (2-hydroxyethyl)-trimethyl-ammonium (choline) and butyl-trimethyl-ammonium cations, identifying the choline-based IL as exhibiting more favorable performance. Notably, the incorporation of additional corrosion inhibitors markedly enhanced the protective properties of these ILs (11).

The design and testing of ammonium-based ILs have yielded encouraging outcomes in corrosion prevention. These ILs display substantial inhibition efficiency, conform to recognized adsorption models, and can be further optimized through the addition of specialized corrosion inhibitors. Collectively, the findings affirm the promise of ammonium-based ILs as effective and environmentally responsible solutions for protecting metal surfaces in acidic environments.

- Brönsted acid ionic liquids

Brönsted acid ionic liquids (BAILs) have been developed and investigated for their effectiveness as corrosion inhibitors for carbon steel in acidic conditions. These innovative ILs, which contain multiple Brönsted acid functional groups, were synthesized with high efficiency (≥98%) and evaluated through a combination of electrochemical techniques and surface characterization methods (12). The tailored cation structure—featuring one phenyl ring and two imidazolium units—enables BAILs to act as mixed-type inhibitors by adhering to steel surfaces and mitigating both anodic and cathodic reactions (12).

Notably, BAILs exhibit excellent corrosion inhibition performance in acidic media regardless of their Brönsted acidity. This challenges the conventional expectation that acidity would hinder inhibitor performance, thereby broadening the scope of BAILs in industrial use (12). In parallel, other ILs such as protic ionic liquids (PILs) and imidazolium-based variants have also shown significant corrosion-inhibiting capabilities in environments like neutral chloride and hydrochloric acid solutions (3, 13).

The synthesis and analysis of BAILs have confirmed their effectiveness as corrosion inhibitors for carbon steel. Their distinctive structure and adsorption behavior promote the formation of protective layers on metal surfaces, consistent with the Langmuir adsorption isotherm (12). These advancements in ionic liquid design present valuable opportunities for improving corrosion resistance in harsh acidic settings, with potential benefits for industrial durability and material longevity.

3. Mechanisms of corrosion inhibition by ionic liquids

- Adsorption Behavior: Physisorption and Chemisorption

Room-temperature ionic liquids (RTILs) have proven effective in mitigating corrosion through a range of mechanisms, with adsorption onto metal surfaces being particularly significant. This adsorption can occur via both physisorption and chemisorption, depending on the nature of the ionic liquid and the metal involved. Physisorption involves relatively weak interactions, such as electrostatic forces and van der Waals attractions. For example, imidazolium-based RTILs with ethyl side chains have been shown to adsorb onto carbon steel surfaces, thereby lowering corrosion rates in aqueous monoethanolamine environments used for CO_2 capture (1). The adsorption of RTIL cations and anions forms a barrier layer on the metal, preventing contact with corrosive agents.

In contrast, chemisorption entails the formation of stronger, more stable chemical bonds between the RTIL and the metal surface. This results in more robust and enduring corrosion inhibition. A notable instance is the hydrogen evolution reaction (HER) on platinum electrodes, where the addition of [Emim]-based RTILs to alkaline media led to their pre-adsorption on the electrode. This stabilized intermediate hydrogen species and influenced both adsorption and charge transfer dynamics at the metal-electrolyte boundary (14).

The corrosion-inhibiting efficiency of RTILs is influenced by several parameters, such as the nature and concentration of the constituent ions. Among the studied options, [emim][acetate] demonstrated superior performance in reducing corrosion rates in CO_2 capture systems that utilize alkanolamines (1). Additionally, factors like alkyl chain length on the cation can affect adsorption behavior, as shown in chromatographic analyses where longer chains increased hydrophobic interactions with stationary phases (15).

- Mixed-type inhibition

Ionic liquids (ILs) have shown considerable potential as corrosion inhibitors for a range of metals exposed to different corrosive environments. Numerous studies have indicated that ILs generally function as mixed-type inhibitors, simultaneously affecting both anodic and cathodic processes on the metal surface (3).

The primary mechanism behind their corrosion inhibition is the adsorption of IL molecules onto the metal surface, leading to the formation of a protective film that blocks the penetration of corrosive agents. This adsorption can involve a combination of physical and chemical interactions between the ILs and the substrate (8). Often, this process adheres to the Langmuir adsorption isotherm model, suggesting a monolayer adsorption of ILs across the metal surface (16).

A range of factors influences the inhibition efficiency of ILs, including their molecular configuration, concentration, and the specific properties of the corrosive medium. For example, elongating the alkyl chain in imidazolium-based ILs has been found to enhance their inhibitory performance (5). Furthermore, innovative approaches—such as the use of polymeric ILs and IL-loaded microspheres—have been developed to provide advanced corrosion protection through synergistic actions and pH-sensitive release systems (8; 17).

ILs inhibit corrosion through a mixed-type mechanism involving their adsorption onto metal surfaces, which disrupts both anodic and cathodic reactions. Their overall efficiency is governed by structural and environmental factors, and continued research is focused on designing new ILs and delivery systems to optimize their protective capabilities across varied conditions.

- Protective layer formation

Ionic liquids (ILs) effectively inhibit corrosion by forming protective films on metal surfaces. The adsorption of IL species establishes a barrier that shields the metal from aggressive environments (18). This protective layer arises from several mechanisms, including electrostatic attraction, proton transfer, and electron donor-acceptor interactions (8).

The morphology and composition of these protective layers can differ based on the IL used. For example, certain ILs generate a stratified structure with a compact layer adjacent to the metal surface, a porous intermediary layer, and a flake-like outer region (19). Additionally, the creation of surface-bound metal-IL complexes contributes to enhanced corrosion resistance (20). The

adsorption behavior of both IL cations and anions is central to this process—bromide and imidazolate anions, along with vinylimidazolium cations, have been particularly effective in promoting strong surface interactions (20).

ILs offer corrosion protection primarily through film formation via adsorption and the development of complex surface compounds. Their performance is influenced by variables such as IL concentration, temperature, and the specific pairing of metal and IL. The ability to tailor ILs for specific functions by modifying anion or cation structures enables the customization of interfacial properties, making them highly adaptable and promising for corrosion control across a wide range of industrial applications (21).

4. Factors affecting inhibition efficiency

- Concentration dependence

The corrosion inhibition efficiency of ionic liquids (ILs) typically improves with increasing concentration, as evidenced by numerous studies: At elevated concentrations, ILs are more likely to form compact and uniform protective layers on metal surfaces, enhancing corrosion resistance. For instance, the performance of Quaternium-32 increased with concentration, achieving up to 94% efficiency at 20 μmol/L (22). Similarly, the polymeric IL PDBA-IL-NH_2 demonstrated a steady rise in inhibition efficiency with concentration, reaching a maximum of 94.67% at 100 ppm (8). However, this concentration-efficiency relationship is not strictly linear. In the case of imidazolium-based ILs, a notable rise in efficiency occurred below the critical micelle concentration (CMC), but further increases beyond the CMC did not yield additional improvements. This is attributed to the saturation of adsorption sites on the metal surface (23). Such behavior indicates that each IL has an optimal concentration range for peak performance.

Although increasing IL concentration generally enhances corrosion protection, phenomena like micelle formation and adsorption saturation must be considered. Identifying the optimal concentration for each IL through experimental evaluation is essential for maximizing efficiency while maintaining cost-effectiveness. This understanding plays a critical role in designing practical corrosion inhibition systems using ILs.

- Temperature effects

Temperature has a significant influence on the corrosion inhibition efficiency of ionic liquids (ILs), with most studies indicating a decline in performance as temperature increases. For example, Quaternium-32 (Q-32) showed reduced inhibition efficiency at elevated temperatures (23). Likewise, imidazolium-based ILs with varying alkyl chain lengths (R8, R10, R12) exhibited increased corrosion rates and diminished effectiveness when the temperature rose from 20°C to 50°C (5). Similar findings were reported for vinylimidazolium-based poly(ionic liquid)s, which reached their peak inhibition efficiency (75%) at 308 K, beyond which performance decreased (20). However, not all ILs follow this trend. In some cases, higher temperatures led to enhanced inhibition. For instance, 1-butyl-3-methylimidazolium trifluoromethyl sulfonate ([BMIm]TfO) displayed a progressive increase in efficiency as the temperature increased from 303 K to 333 K (24). Conversely, 1-methyl-1-propyl-piperidinium bromide (MPPB) experienced a drop in performance at elevated temperatures, with a maximum efficiency of 60% observed at 308 K (25).

Overall, temperature is a key parameter affecting the performance of IL-based corrosion inhibitors. While many ILs demonstrate decreased efficiency at higher temperatures due to desorption or accelerated corrosion kinetics, others may benefit from improved mobility or

enhanced adsorption. Careful evaluation of temperature effects is essential for selecting and optimizing ILs for use in temperature-variable environments.

- Molecular structure influence

The corrosion inhibition efficiency of ionic liquids (ILs) is heavily influenced by their molecular architecture, particularly the structure of their cationic and anionic components. One of the most critical factors is the alkyl chain length on the cation. Studies have shown that increasing the alkyl chain length in 1-alkyl-3-methylimidazolium bromide ILs enhances inhibition efficiency, likely due to stronger surface interactions and the formation of more compact adsorption layers on the metal substrate (23). Additionally, the nature of the cation plays a key role, with imidazolium-based ILs frequently outperforming other cation types in corrosion inhibition (8)(26). The identity of the anion also affects performance. For example, a comparison between 1-butyl-3-methylimidazolium chloride and bromide revealed differences in inhibition efficacy, underscoring the influence of anion chemistry on surface interactions (18). Moreover, functional groups attached to the cationic side chain can increase electron-donating capacity, enhancing adsorption onto metal surfaces (27). IL concentration is another important factor—efficiency generally improves with increasing concentration up to a threshold often associated with the critical micelle concentration (23).

In summary, the inhibition efficiency of ILs is governed by the structural characteristics of both their cations and anions, including alkyl chain length, type of functionalization, and ionic composition. Understanding these molecular-level relationships is essential for the rational design of high-performance, sustainable corrosion inhibitors based on ionic liquids.

5. Advanced applications of ionic liquids in corrosion inhibition

-Smart Corrosion Inhibitors Using Chitosan Microspheres

Ionic liquids (ILs) have opened new avenues in corrosion protection, particularly through the development of smart corrosion inhibitors. A notable example involves chitosan microspheres loaded with synthesized Gemini imidazolium-based ILs—specifically [C2(Bim)2]Cl2@CSM and [C6(Bim)2]Br2@CSM—designed for protecting N80 steel in hydrochloric acid. These systems achieved high inhibition efficiencies of 94.68% and 95.96%, respectively, at a concentration of 300 mg L^{-1} (17). What sets these microspheres apart is their pH-responsive behavior, enabled by Schiff-base C=N bonds. This feature allows the ILs to be rapidly released in acidic environments, such as corrosion sites, where they synergize with decomposed microspheres to enhance protective action (17). In comparison, room-temperature ionic liquids (RTILs) like [emim][acetate] have also shown corrosion mitigation capabilities, particularly in monoethanolamine-based CO_2 capture systems (1).

Incorporating ILs into smart delivery systems like chitosan microspheres represents a significant advancement in targeted corrosion inhibition. These responsive systems enable precise delivery and improved efficiency, highlighting the adaptability of ILs for diverse industrial applications.

-Polymeric Ionic Liquids

Polymeric ionic liquids (PILs) are gaining traction as high-performance corrosion inhibitors, offering distinct advantages over traditional and monomeric ILs. One such PIL, PDBA-IL-NH2—synthesized using short-chain imidazolium IL monomers—demonstrated excellent inhibition efficiency, reaching 94.67% at 100 ppm for mild steel (8). Notably, PDBA-IL-NH2 outperformed

its counterparts, including PDBA-IL-OH, PIL-NH2, and IL-NH2, under identical conditions (8). The corrosion protection efficiency of PILs is closely tied to their composition. For example, PILs developed from chitosan and various fatty acids exhibited differing performance, with the inhibition order being CSPTA-lauric > CSPTA-myristic > CSPTA-palmitic > CSPTA-stearic (28). This suggests that tailoring the fatty acid component can significantly influence the overall inhibition behavior.

PILs present a promising direction for developing sustainable and effective corrosion inhibitors. Their customizable structure, superior performance, and potential for smart functionality make them ideal candidates for future corrosion protection technologies. Continued research into their structural optimization and mechanism of action is likely to yield even more effective solutions.

6. Comparative studies of ionic liquids with other inhibitors

-Surfactants

Ionic liquids (ILs) share notable similarities with surfactants in their physicochemical behaviors, including self-assembly and micelle formation. However, ILs often exhibit a higher degree of self-organization, especially in long-range ordering, due to their ionic nature and tunable structures (29). Studies on the critical micelle concentration (CMC) of surfactant-IL systems highlight the crucial role of interfacial energy in surfactant aggregation, with the extent of this effect largely dependent on the structure of the IL used (30).

Some ILs, such as those based on pyrrolidinium cations, resemble surfactants in structure and behavior, forming local aggregates that can influence ion mobility and conductivity—properties important for electrochemical applications (31). In recent developments, surface-active ionic liquids (SAILs) have emerged, integrating the advantages of ILs and surfactants. These SAILs offer enhanced performance across a variety of applications, including chromatography, extraction processes, and wood protection (32)(33).

While ILs and surfactants share overlapping characteristics, ILs provide greater structural tunability. This versatility is especially evident in SAILs, which outperform conventional surfactants in several domains. Their adaptability makes them promising candidates for future applications in enhanced oil recovery, CO_2 capture, and other environmentally demanding processes (34).

- Traditional corrosion inhibitors

Comparative studies between ionic liquids (ILs) and traditional corrosion inhibitors often focus on their environmental impact, physical properties, and inhibition performance. While specific inhibition efficiencies can vary greatly depending on the metal, corrosive medium, concentration, and temperature, a general comparison of their characteristics and performance is possible. The following table summarizes the key comparative features.

Table 1. Comparative Studies of Ionic Liquids and Traditional Corrosion Inhibitors

Feature	Ionic Liquids (ILs)	Traditional Organic/Inorganic Inhibitors
Environmental Impact & Toxicity	Generally considered "**greener**" alternatives. Lower toxicity (especially new generations). **Negligible vapor pressure** (non-volatile), minimizing air pollution.	Many organic inhibitors (e.g., those containing heavy metals, volatile amines) can be **highly toxic** or environmentally damaging. Often possess **high volatility**.

Corrosion Inhibition Efficiency	Often exhibit **high and comparable, or even superior, inhibition efficiencies** (frequently \gt 90\%) at relatively low concentrations.	Efficiency is highly variable, but many conventional inhibitors also show high efficiency. Performance can degrade faster in harsh conditions.
Tunability and Versatility	**Highly tunable** and "task-specific." The cation and anion can be modified independently to optimize for a specific metal, medium, or temperature.	Limited tunability. Chemical structure is more rigid, offering less scope for fine-tuning properties for specific applications.
Physical and Chemical Stability	Exhibit **excellent thermal and chemical stability** over a wide range of temperatures and pressures, which is advantageous for high-temperature and high-pressure industrial processes.	Thermal stability is often lower, which can limit their application in harsh industrial environments.
Mechanism of Action	Typically function as **mixed-type inhibitors** (affecting both anodic and cathodic reactions). Adsorption involves **both the organic cation and the anion** on the metal surface.	Primarily form a protective barrier via adsorption of the organic molecule (often involving heteroatoms like N, S, O). Many are either anodic or cathodic-specific.
Volatility	**Non-volatile** (negligible vapor pressure).	Many are volatile, contributing to potential environmental and health hazards.
Cost and Availability	Currently, their **high synthesis cost** is a major drawback, though this is decreasing as production scales up.	Generally **less expensive** and widely commercially available.
Solubility	**High solubility and compatibility** with many organic and inorganic substances. Can be designed to be miscible or immiscible with specific solvents.	Solubility can be limited, especially for organic inhibitors in aqueous or highly polar media.

The primary motivation for using ionic liquids over traditional inhibitors stems from their superior environmental profile (non-volatility and lower toxicity) and their structural tunability, which allows for the creation of "designer" inhibitors with high thermal stability and performance tailored to specific corrosive conditions.(33)34)(35)

7. Plant Extracts and Pharmaceutical Drugs

Ionic liquids (ILs) are increasingly recognized alongside plant extracts and pharmaceutical drugs as effective organic green corrosion inhibitors (OGCIs). These inhibitors are appreciated for their eco-friendliness, biodegradability, and cost-effectiveness (35). Comparative studies indicate that ILs perform effectively in various corrosive environments, such as hydrochloric acid and brackish water (36)(37). Unlike plant extracts and pharmaceuticals, ILs exhibit multifunctional properties. Beyond corrosion inhibition, ILs have been applied in drug solubilization, targeted delivery, and even as active pharmaceutical ingredients (API-ILs) (38)(39)(40). This broader utility provides ILs with a unique advantage in multidisciplinary applications.

Nonetheless, it is important to consider the potential environmental toxicity of ILs when evaluating them against other OGCIs (41). The selection of an appropriate inhibitor should balance efficiency, cost, environmental impact, and application-specific requirements.

8. Electrochemical Techniques for Evaluating Ionic Liquids

- Electrochemical Impedance Spectroscopy (EIS)

EIS is a widely used technique to assess the corrosion inhibition performance of ionic liquids. It provides insights into the electrochemical processes at the metal-electrolyte interface and evaluates the formation and stability of protective films (12)(42). Key parameters such as charge transfer resistance (Rct) and double-layer capacitance (Cdl) are measured—an increase in Rct and decrease in Cdl typically signify improved corrosion resistance (43).

In more complex systems like concrete, EIS interpretation can be challenging due to overlapping signals from multiple phenomena. Innovative methods, such as analyzing characteristic relaxation angular frequencies and employing odd random phase EIS (ORP-EIS), have been proposed to overcome these limitations and study time-dependent behavior (44)(45). EIS offers detailed insights into inhibition mechanisms and complements other electrochemical and surface techniques for a holistic evaluation of IL-based inhibitors (28)(46)(47).

- Potentiodynamic Polarization

Potentiodynamic polarization is another essential technique for evaluating ILs as corrosion inhibitors. It helps elucidate corrosion behavior and inhibition mechanisms across various metal surfaces. For example, pyrrolidinium ILs demonstrated inhibition efficiencies up to 85% for copper in 1 M HNO_3 at a concentration of 0.05 mM (42). Imidazolium and pyridinium ILs similarly showed high efficiency in inhibiting steel corrosion in 1 M HCl, with performance increasing alongside concentration (6). Many ILs function as mixed-type inhibitors, reducing both anodic and cathodic reactions, as seen with Brönsted acid ILs on carbon steel and other imidazolium-based ILs (12)(6). However, some chloride-containing ILs failed to develop a passive region on 1018 carbon steel, as evident in anodic polarization curves (48), indicating that IL composition critically affects inhibition behavior.

- Weight Loss Method

The weight loss method remains a foundational technique for quantifying corrosion rates and evaluating inhibitor efficiency. It involves comparing the mass of a metal sample before and after exposure to a corrosive environment with and without the IL. Numerous studies have confirmed its effectiveness. Pyrrolidinium ILs provided up to 85% inhibition for copper in 1 M HNO_3, and similar results were observed for imidazolium and pyridinium ILs in acidic environments (6)(42). In carbon steel immersed in 3.5% NaCl, 1-butylpyrrolidinium chloride also demonstrated significant inhibition based on weight loss measurements (49). The weight loss method is frequently corroborated by results from polarization studies, reinforcing its reliability in assessing IL performance (6).

9. Surface Analysis Techniques for Studying Inhibition Mechanisms

- Scanning Electron Microscopy (SEM)

SEM is instrumental in analyzing the morphology and topography of metal surfaces before and after corrosion. It delivers nanometer-scale resolution, making it ideal for visualizing the physical effects of corrosion and the presence of protective inhibitor films (50)(51). Advanced SEM setups, including environmental SEM, allow imaging under moist or high-pressure conditions with minimal resolution loss (52). Coupling SEM with complementary techniques such as Auger electron spectroscopy and NMR relaxometry enables multidimensional material characterization, as seen in studies of hydrated cement and corrosion-affected metals (53).

- X-ray Photoelectron Spectroscopy (XPS)

XPS provides chemical state and compositional data for the top few nanometers of a surface. It is particularly valuable for identifying adsorbed inhibitor species, quantifying elemental content, and analyzing surface interactions relevant to inhibition (54)(55).

The technique is highly sensitive, detecting as low as 0.1 atomic % and all elements except hydrogen and helium (54). XPS can reveal the formation of new chemical bonds or interaction sites indicative of successful inhibitor adsorption (56)(57). Although traditional XPS requires ultra-high vacuum conditions, modern near-ambient pressure XPS (NAP-XPS) enables surface analysis under more realistic environmental conditions (58). Despite the challenges in sample preparation and data interpretation, XPS remains indispensable in corrosion science and surface chemistry (59)(60)(61).

10. Industrial applications and future prospects

- Electroplating

Ionic liquids (ILs) have emerged as promising alternatives to conventional electrolytes in industrial electroplating processes due to their unique physicochemical properties. Composed entirely of ions, ILs offer several advantages over aqueous electrolytes, including lower toxicity, wider electrochemical windows, higher thermal stability, and improved current efficiencies (62). These features make ILs particularly attractive for sustainable electroplating applications and corrosion protection strategies.

In electroplating, ILs have been successfully employed for the electrodeposition of metals and alloys such as zinc and zinc–nickel, which are extensively used in the automotive and aerospace sectors to protect steel components from corrosion (63). Notably, deep eutectic solvents—a subclass of ILs—have been used to deposit nanocrystalline nickel coatings with superior mechanical properties, enhanced corrosion resistance, and improved electrolyte stability (64). Moreover, the electrodeposition of aluminum and aluminum–platinum alloys from room-temperature ILs has been demonstrated, showcasing reduced water sensitivity and simplified purification, thereby enhancing process efficiency and reducing costs (2).

Looking forward, the design of task-specific ionic liquids—where the anion or cation chemistry is tailored for specific electrochemical applications—offers exciting opportunities. Such precision engineering enables better control of metal deposition, surface morphology, and interfacial interactions, which are crucial for advanced material applications (21). The inherently wide electrochemical windows of many ILs (often exceeding 5 V) further extend their usability in high-voltage electrochemical systems (65). However, despite their advantages, the industrial-scale adoption of IL-based electroplating processes remains limited due to unresolved challenges in cost, stability, and scalability (62)(63).

Challenges and Opportunities in Large-Scale Applications

In addition to electroplating, ionic liquids have garnered attention as effective corrosion inhibitors across various industries. Numerous studies have highlighted the ability of ILs to reduce corrosion rates on metals such as carbon steel and stainless steel, especially in aggressive environments like acidic or saline media (6)(10)(66). Their inhibition efficiency is strongly influenced by molecular structure and concentration, with higher concentrations often resulting in greater surface coverage and protection (8)(10).

ILs inhibit corrosion primarily through adsorption mechanisms, forming protective films on metal surfaces. This behavior often conforms to the Langmuir adsorption isotherm model, indicating monolayer adsorption with uniform energy sites (6)(10)(37). Such protective behavior is advantageous for dynamic and corrosive industrial settings. However, scaling up the application of ILs for real-world corrosion protection presents several challenges. Laboratory results may not directly translate to complex industrial environments—such as high-temperature, high-pressure, and high-salinity conditions found in oil and gas reservoirs—where inhibitor stability and persistence become critical concerns (67). Additionally, the synthesis of ILs, which often involves multi-step processes and expensive precursors, can hinder their commercial feasibility.

On the positive side, advances in green chemistry and materials science are paving the way for the development of cost-effective, biodegradable, and task-specific ILs. These innovations aim to reduce toxicity, improve environmental compatibility, and tailor properties for specific corrosion systems (68). Continued research into the structure–activity relationships and environmental behavior of ILs will be key to unlocking their full industrial potential (11)(8).

Conclusion

Ionic liquids offer transformative possibilities in both electroplating and corrosion inhibition, combining versatility with environmental and performance benefits. While challenges remain—particularly regarding scalability, cost, and complex operating conditions—ongoing research in green synthesis, tailored IL design, and hybrid applications provides a path forward. As the field of ionometallurgy matures, ILs are expected to play a central role in next-generation surface engineering technologies, especially where traditional methods fall short.

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