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Modified Cellulose-Based Materials as Green Corrosion Inhibitors for Mild Steel in Acidic Media: A Review

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Abstract

The increasing demand for eco-friendly corrosion protection has driven significant research into cellulose-based materials as sustainable inhibitors for mild steel in acidic environments. This review comprehensively examines the structural characteristics, chemical and physical modifications, and nanostructured forms of cellulose that enhance its adsorption, film-forming, and corrosion inhibition properties. Mechanisms such as physisorption, chemisorption, electrostatic interactions, and functional-group coordination are analyzed, alongside experimental and computational approaches used for performance evaluation. Challenges, including stability under harsh conditions, cost and scalability of modification, reproducibility, and limited long-term data are highlighted. The integration of experimental findings with computational modeling provides insights into the rational design of efficient, green corrosion inhibitors. Future perspectives emphasize the development of standardized protocols, long-term performance assessment, and industrial applications to advance sustainable corrosion protection technologies.

Keywords: Cellulose derivatives, Corrosion inhibition, Mild steel, Acidic media, Green inhibitors, Nanocellulose, Adsorption mechanisms

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1. Introduction

Corrosion is a naturally occurring process that results in the gradual deterioration of metals through chemical or electrochemical interactions with their surrounding environment. This phenomenon represents a major challenge in both industrial and economic contexts, as it leads to structural failure, reduced operational efficiency, and increased costs associated with maintenance, repair, and replacement of materials (Husaini, 2024a-c). Industries such as construction, transportation, oil and gas, and manufacturing are particularly affected, with corrosion-related losses accounting for a significant portion of global economic expenditure (Talha, 2024). Consequently, the development of effective corrosion prevention and control strategies remains a critical priority for ensuring the

longevity, safety, and reliability of metallic systems (Aourabi *et al.,* 2021; Verma *et al.,* 2023; Guendouz *et al.,* 2025).

Mild steel, due to its low cost, availability, and favorable mechanical properties, is one of the most widely used engineering materials. However, it is highly vulnerable to corrosion, especially in acidic environments. Such environments are commonly encountered in industrial processes like acid pickling, descaling, and oil well acidizing, where acids are used to remove scale, rust, and other impurities (Ahmed *et al.,* 2024; Ech-chihbi *et al.,* 2024; Salim *et al.,* 2024). Under these aggressive conditions, the rate of metal dissolution increases significantly, leading to rapid degradation if protective measures are not implemented (Obot and Ankah, 2023). This high susceptibility highlights the importance of developing efficient and reliable corrosion inhibition strategies for mild steel in acidic media.

Conventional corrosion inhibitors, often based on synthetic organic or inorganic compounds, have been widely employed to mitigate corrosion in acidic environments (Bouklah *et al.,* 2006; Husaini, 2024a-c). While these inhibitors can provide high efficiency, they are frequently associated with several drawbacks, including toxicity, environmental persistence, and high cost. Many of these substances pose risks to human health and ecosystems, prompting stricter environmental regulations and growing concerns over their long-term use (Kumar *et al.,* 2024). These limitations have encouraged researchers to explore safer, cost-effective, and environmentally sustainable alternatives that can offer comparable or improved performance (Rizi *et al.,* 2023; Husaini, 2026).

In recent years, green corrosion inhibitors derived from natural and renewable resources have gained increasing attention as viable substitutes for conventional inhibitors. Among these, cellulose stands out as a particularly promising material due to its abundance, biodegradability, non-toxic nature, and low cost. Sourced from plant biomass and other natural materials, cellulose contains abundant hydroxyl groups that can be chemically modified to enhance adsorption on metal surfaces (Husaini, 2025a; Singh *et al.,* 2023). These modifications improve its ability to form protective films, thereby reducing corrosion rates. Additionally, the adaptability of cellulose allows for the development of advanced derivatives, composites, and nanostructured forms with enhanced inhibition efficiency (Husaini, 2025b; Zhang *et al.,* 2024a).

This review aims to provide a comprehensive and up-to-date overview of modified cellulose-based materials as eco-friendly corrosion inhibitors for mild steel in acidic environments. It focuses on the structural characteristics and modification strategies of cellulose, examines the mechanisms of corrosion inhibition, and evaluates performance using both experimental and theoretical approaches. Furthermore, the review discusses practical applications, identifies key challenges and limitations, and

highlights future research directions aimed at advancing sustainable corrosion protection technologies (Solomon *et al.,* 2023).

2. Cellulose as a Green Material

2.1 Structure and Properties of Cellulose

Cellulose is a naturally occurring polysaccharide composed of repeating β-1,4-linked D-glucose units. This linear arrangement enables extensive intermolecular and intramolecular hydrogen bonding, resulting in a highly ordered crystalline structure that imparts notable mechanical strength and thermal stability. These structural characteristics make cellulose resistant to harsh chemical environments, which is advantageous for applications in corrosion inhibition (Verma *et al.,* 2024). Beyond its structural robustness, cellulose is abundant in nature, fully renewable, and readily biodegradable, making it an environmentally sustainable choice (Deng *et al.,* 2024). The polymer's hydroxyl groups are chemically reactive, offering multiple sites for functionalization, which can significantly enhance its adsorption behavior and performance when applied as a green corrosion inhibitor (Husaini et al, 2025a; Samir and El-Sayed, 2023).

2.2 Sources of Cellulose

Cellulose is obtained from a wide variety of natural sources. Plant-based cellulose is the most common, found in wood, cotton, hemp, and agricultural residues, which are often considered low-cost and renewable feedstocks (Raza *et al.,* 2024). These sources offer high cellulose content and can be processed into micro- or nanocellulose for specialized applications (Sonowal and Wani, 2025). In addition, bacterial cellulose, produced via microbial fermentation by strains such as *Acetobacter xylinum*, exhibits superior purity, high crystallinity, and a unique three-dimensional nanofibrous network (Dagnino *et al.,* 2025). This nanostructured cellulose possesses a high surface area and excellent water-holding capacity, which is particularly beneficial for forming protective films on metal surfaces (Liu *et al.,* 2023). The availability of diverse sources allows researchers to select and tailor cellulose materials according to specific performance requirements (Wang *et al.,* 2025).

2.3 Advantages in Corrosion Inhibition

Cellulose-based materials present multiple advantages as green corrosion inhibitors. Their non-toxic and environmentally friendly nature addresses the growing concerns associated with conventional synthetic inhibitors, which often pose health and ecological risks (Ariffin *et al.,* 2024). The presence of abundant hydroxyl groups in the cellulose backbone facilitates chemical modifications, such as esterification, etherification, or grafting of heteroatoms (N, S, O), which improve adsorption on metal

surfaces and enhance inhibition efficiency (Răuță, 2025). Moreover, cellulose exhibits excellent film-forming properties, enabling it to create uniform protective layers that act as physical barriers against corrosive agents (Verma *et al.,* 2024). The combination of chemical tunability, film-forming ability, and biodegradability makes cellulose an attractive material for sustainable corrosion protection strategies in acidic and aggressive environments (Wang *et al.,* 2025).

3. Modification of Cellulose for Corrosion Inhibition

3.1 Chemical Modification

Chemical modification of cellulose involves introducing new functional groups into its polymeric backbone to improve its chemical reactivity and adsorption on metal surfaces. Common methods include carboxylation**,** etherification**,** and esterification, which attach carboxyl, ether, or ester groups to cellulose chains, increasing the density of active sites. These functional groups facilitate stronger interaction with metallic surfaces through hydrogen bonding or coordination with metal ions (Deng *et al.,* 2024). Additionally, incorporating heteroatoms such as nitrogen, sulfur, or oxygen enhances electron donation to metal atoms, strengthening chemisorption and forming a more stable protective film. Such modifications are essential for achieving higher corrosion inhibition efficiency, particularly in aggressive acidic environments where unmodified cellulose may be less effective (Husaini, 2025c).

3.2 Physical and Surface Modification

Physical or surface modifications enhance the performance of cellulose without changing its primary chemical structure. Techniques such as surface functionalization allow for the attachment of active moieties or fillers, increasing surface energy and promoting better adhesion to metal substrates. Cross-linking is another key approach, where polymer chains are interconnected to form a three-dimensional network, improving mechanical stability, thermal resistance, and structural integrity. These physical enhancements not only strengthen the cellulose film but also increase its resistance to chemical attack, resulting in a more uniform and long-lasting barrier that effectively slows down corrosion processes on mild steel (Verma *et al.,* 2024).

3.3 Nanostructured Cellulose Materials

Nanostructured cellulose, including cellulose nanocrystals (CNCs)**,** cellulose nanofibers (CNFs), and cellulose nanoparticles, has gained significant attention in corrosion inhibition due to its nanoscale properties. These materials exhibit a high surface-to-volume ratio, which maximizes the contact area with the metal surface and improves adsorption efficiency. Nanocellulose can form compact, dense films that act as effective physical barriers against corrosive ions. Additionally, the surface chemistry

of nanocellulose can be easily tailored via functionalization, further enhancing its protective ability. The combination of nanoscale morphology and chemical tunability makes nanostructured cellulose an attractive option for advanced green corrosion inhibitors (Wang *et al.,* 2025).

3.4 Composite and Hybrid Materials

Creating composite and hybrid cellulose materials combines the intrinsic advantages of cellulose with the functional properties of other materials to achieve synergistic effects. Cellulose–metal oxide composites exploit the reactivity and catalytic properties of metal oxides while benefiting from the film-forming ability and renewability of cellulose. These composites can provide dual protection by forming both chemical and physical barriers. Similarly, polymer–cellulose hybrids integrate synthetic or biodegradable polymers with cellulose to enhance flexibility, mechanical strength, and long-term stability of coatings. Such hybrid materials are highly adaptable, allowing formulation adjustments for specific industrial applications, such as pickling, descaling, or oil well acidizing, where both durability and environmental safety are critical (Kang *et al.,* 2025).

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4. Mechanisms of Corrosion Inhibition

4.1 Adsorption Mechanisms

Adsorption is a fundamental step in corrosion inhibition, playing a critical role in protecting mild steel in acidic environments. Inhibitor molecules attach to the metal surface, forming a layer that prevents aggressive ions from reaching the metal. This process can occur through physisorption, involving weak van der Waals forces, or chemisorption, which involves stronger chemical bonds, often facilitated by heteroatoms such as nitrogen, oxygen, or sulfur present in the inhibitor molecules (Kamboj *et al.,* 2026; Husaini, 2023a&b). The adsorption behavior is influenced by the inhibitor's molecular structure, the metal's surface charge, temperature, and solution pH. In acidic solutions, the adsorption process can involve the displacement of water molecules coordinated to the metal surface or the formation of coordinate bonds through lone pairs of electrons on heteroatoms (Castillo-Robles *et al.,* 2024).

Reactions:

$M–H_2O + Inhibitor \rightleftharpoons M–Inhibitor + H_2O$

$M + Inhibitor–NH_2 \rightarrow M–NH_2$

$M + Inhibitor–H^+ \rightarrow M–Inhibitor–H^+$

4.2 Film Formation

After adsorption, inhibitors can form a continuous protective barrier on the metal surface, minimizing the contact between H^+, Cl^-, and other corrosive ions with the steel. This barrier may exist as a monolayer or multilayer stabilized by hydrogen bonding, van der Waals forces, or π–π interactions between inhibitor molecules (Jero *et al.,* 2024; Didam *et al.,* 2025). The formation of such a protective film effectively blocks the adsorption of corrosive ions, thereby preventing the formation of soluble metal salts and producing a more stable metal–inhibitor complex.

Reactions:

$n\ M + n\ Inhibitor \rightarrow M–Inhibitor\ (monolayer)$

$M–Inhibitor + Inhibitor \rightarrow M–Inhibitor–Inhibitor\ (multilayer)$

$Fe^{2+} + 2\ Cl^- \rightarrow FeCl_2\ (without\ inhibitor)$

$Fe^{2+} + Inhibitor \rightarrow Fe–Inhibitor\ (protected)$

4.3 Role of Functional Groups

The efficiency of cellulose-based or other organic inhibitors largely depends on the presence and type of functional groups, such as –OH, –COOH, and $–NH_2$. These groups facilitate strong interactions

with the metal surface through coordination or hydrogen bonding, leading to more robust and uniform adsorption (Zhang *et al.,* 2024b; Husaini *et al.,* 2025b; Peter *et al.,* 2025). Hydroxyl groups can form coordinate bonds with iron atoms, carboxyl groups may stabilize the adsorbed layer through hydrogen bonding, and aromatic systems in inhibitor molecules can participate in π–metal interactions. These interactions ensure firm attachment, providing sustained protection against acid attack.

Reactions:

Fe + Inhibitor–OH → Fe–O–Inhibitor

Fe–OH + Inhibitor–COOH → Fe–OH···O=C–Inhibitor

Fe + Aromatic ring → Fe···π–Aromatic

4.4 Electrostatic and π–π Interactions

Electrostatic interactions between charged inhibitor molecules and the oppositely charged metal surface enhance the adsorption process, especially in acidic solutions where protonation occurs. In addition, π–π stacking interactions between aromatic rings of adjacent inhibitor molecules contribute to the formation of multilayer films with higher density and improved integrity. These physical interactions, combined with chemical bonding and film formation, create a comprehensive barrier that prevents H^+ ions from reaching the metal surface, thereby enhancing corrosion resistance under aggressive acidic conditions (Wang *et al.,* 2023; Ahmed *et al.,* 2024).

Reactions:

$M^{\delta+}$ + $Inhibitor^{\delta-}$ → M–Inhibitor (adsorbed)

$Inhibitor_1$ + $Inhibitor_2$ → $Inhibitor_1$···$Inhibitor_2$

Fe + H^+ → No reaction (protected by inhibitor layer)

5. Experimental and Characterization Techniques

5.1 Weight Loss Measurements

Weight-loss measurements are among the simplest and most widely used methods for evaluating the corrosion inhibition efficiency of various compounds on mild steel. This method involves immersing pre-weighed steel specimens of known dimensions into acidic solutions with varying inhibitor concentrations for a specified time (Hmamou *et al.,* 2013; Husaini, 2020a&b). After immersion, the samples are carefully removed, cleaned to eliminate corrosion products without affecting the underlying metal, dried, and weighed again to determine the mass loss. The weight loss data are used to calculate the corrosion rate (CR) and inhibition efficiency (IE%). This technique is particularly useful for long-term corrosion studies, as it provides cumulative information about material degradation over time (Obot and Ankah, 2023). Additionally, weight loss measurements can serve as

baseline data to validate more advanced electrochemical methods and provide input for kinetic and thermodynamic analyses (Ahmed *et al.,* 2024; Zriouel *et al.,* 2025). The simplicity, cost-effectiveness, and reproducibility of this method make it a standard approach in corrosion research.

$$CR = \frac{\Delta W}{A \times t \times \rho} \quad \textbf{Eqn. 1}$$

$$IE\% = \frac{CR_0 - CR_i}{CR_0} \times 100 \quad \textbf{Eqn. 2}$$

Where ΔW is the weight loss (mg), A is the exposed area (cm²), t is the immersion time (h), and ρ is the metal density (g/cm³).

Reactions:

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

Fe + Inhibitor → Fe–Inhibitor

5.2 Electrochemical Methods

Electrochemical methods, such as electrochemical impedance spectroscopy (EIS) and Tafel polarization, provide highly sensitive and quantitative information about corrosion kinetics and inhibition mechanisms. EIS measures the impedance response of the metal–solution interface over a range of frequencies, providing parameters such as charge transfer resistance (R_{ct}) and double-layer capacitance (C_{dl}), which reflect the extent of inhibitor adsorption and the quality of the protective layer (Verma *et al.,* 2023). Tafel polarization studies involve measuring the current response of the metal as the potential is scanned, thereby determining the corrosion current density (i_{corr}) and corrosion potential (E_{corr}), which indicate whether the inhibitor predominantly affects anodic, cathodic, or both reactions (Talha, 2024). These techniques are rapid, reproducible, and provide mechanistic insights that complement weight-loss studies. Correlating electrochemical data with inhibitor concentration, temperature, and exposure time can help elucidate adsorption behavior and inhibitor efficiency under different conditions (Kumar *et al.,* 2024).

$$CR = \frac{0.00327 \times i_{corr} \times EW}{\rho} \quad \textbf{Eqn. 3}$$

Where:

CR = Corrosion rate (mm/year)

i_{corr} = Corrosion current density (μA/cm²)

EW = Equivalent weight of the metal (g/equiv)

ρ = Density of the metal (g/cm³)

0.00327 = Unit conversion constant to get CR in mm/year

$$IE\% = \frac{i^0_{corr} - i_{corr}}{i^0_{corr}} \times 100 \quad \textbf{Eqn. 4}$$

Where:

IE% = Inhibition efficiency (%)

i^0_{corr} = Corrosion current density without inhibitor (μA/cm²)

i_{corr} = Corrosion current density with inhibitor (μA/cm²)

Electrochemical reactions include:

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

Cathodic: $2H^+ + 2e^- \rightarrow H_2$

Overall: $Fe + 2H^+ \rightarrow Fe^{2+} + H_2$

With inhibitor: Fe + Inhibitor → Fe–Inhibitor

5.3 Surface Analysis

Surface analysis techniques provide essential microscopic and molecular-level insights into how inhibitors interact with metal surfaces and form protective films. Scanning electron microscopy (SEM) allows visualization of surface morphology, revealing areas of localized attack, pitting, or uniform corrosion, and helps confirm the effectiveness of inhibitors in preventing damage (Umoren and Solomon, 2023). Atomic force microscopy (AFM) quantitatively measures surface roughness and topography, providing information on the uniformity and thickness of the adsorbed inhibitor layers (El Azzouzi *et al.,* 2022). X-ray photoelectron spectroscopy (XPS) identifies the elemental composition and oxidation states of surface species, confirming the chemical interaction between inhibitor molecules and the metal surface (Fouda *et al.,* 2024). Fourier-transform infrared spectroscopy (FTIR) detects functional groups such as –OH, –COOH, and $–NH_2$, which are critical in coordinating with metal ions and forming stable protective layers (Obot and Ankah, 2023). The combination of these techniques provides strong evidence for adsorption mechanisms, film formation, and the overall corrosion inhibition process.

Surface reactions:

Fe–OH + Inhibitor–OH → Fe–O–Inhibitor

Fe + Inhibitor–NH_2 → Fe–NH_2–Inhibitor

6. Performance Evaluation of Cellulose-Based Inhibitors

6.1 Inhibition Efficiency

The inhibition efficiency (IE%) of cellulose-based inhibitors is a measure of how effectively these compounds reduce the corrosion rate of mild steel in acidic environments. This efficiency depends heavily on several factors, including the concentration of the inhibitor, immersion time, temperature,

acid type and molarity, and the chemical structure of the cellulose derivative. (Husaini, 2021) Increasing the inhibitor concentration enhances surface coverage and promotes the formation of a uniform protective layer that acts as a barrier between the metal and corrosive medium. Temperature can either increase the corrosion rate or affect the adsorption behavior of inhibitor molecules. Functional groups present in modified cellulose, such as hydroxyl (–OH), carboxyl (–COOH), and amino ($–NH_2$) groups, play a crucial role by forming coordinate bonds or hydrogen bonds with the metal surface, improving inhibition efficiency (Verma *et al.,* 2024).

The inhibition efficiency is determined using the following relation:

$$IE\% = \frac{CR_0 - CR_i}{CR_0} \times 100 \qquad \textbf{Eqn. 5}$$

CR_0 is the corrosion rate without inhibitor, and CR_i is the corrosion rate with inhibitor. Understanding these parameters is essential for optimizing inhibitor formulations for industrial applications (Shahnavaz *et al.,* 2025).

Recent studies indicate that cellulose derivatives with functionalized groups show IE% values exceeding 90% in 1 M HCl solutions, demonstrating their potential as eco-friendly inhibitors (Mohammed *et al.,* 2026).

6.2 Adsorption Isotherms

Adsorption isotherms provide crucial insight into how cellulose-based inhibitors attach to metal surfaces. They relate inhibitor concentration to the surface coverage (θ), helping to elucidate the mechanism of inhibition. Common models include Langmuir, Freundlich, and Temkin isotherms. The Langmuir isotherm assumes monolayer adsorption on homogeneous sites without interaction between adsorbed molecules (Deng *et al.,* 2024):

$$\frac{C}{\theta} = \frac{1}{K_{ads}} + C \qquad \textbf{Eqn. 6}$$

The Freundlich isotherm describes adsorption on heterogeneous surfaces, often relevant for polymeric or modified cellulose inhibitors (Fan *et al.,* 2025):

$$\theta = K \times C^{\frac{1}{n}} \qquad \textbf{Eqn. 7}$$

The Temkin isotherm considers interactions between adsorbed molecules, assuming a linear decrease in adsorption energy with surface coverage (Wang *et al.,* 2025):

$$\theta = \frac{1}{a} \times \ln(K \times C) \qquad \textbf{Eqn. 8}$$

Here, C is the inhibitor concentration, θ is the fraction of surface coverage, K_{ads} is the adsorption equilibrium constant, and n and a are isotherm-specific constants. These models assist in distinguishing between physisorption (weak van der Waals interactions) and chemisorption (strong

coordinate bonding), which directly affects the stability and performance of the inhibitor (Raza *et al.,* 2024).

6.3 Kinetics and Thermodynamics

Kinetic and thermodynamic analyses provide a quantitative understanding of inhibitor performance. The activation energy (E_a) is calculated using the Arrhenius equation (Sonowal and Wani, 2025):

$$CR = A \times \exp\left(\frac{-E_a}{RT}\right) \quad \textbf{Eqn. 9}$$

where CR is the corrosion rate, A is the pre-exponential factor, R is the gas constant, and T is the absolute temperature in Kelvin.

Thermodynamic parameters such as Gibbs free energy ($\Delta G°_{ads}$), enthalpy ($\Delta H°$), and entropy ($\Delta S°$) describe the spontaneity, heat exchange, and disorder associated with adsorption (Abdelhamid, 2024):

$$\Delta G°_{ads} = -R \times T \times \ln(K_{ads}) \quad \textbf{Eqn. 10}$$

$$\ln(K_{ads}) = \frac{\Delta H^0}{RT} + \frac{\Delta S^0}{R} \quad \textbf{Eqn. 11}$$

A negative $\Delta G°_{ads}$ indicates spontaneous adsorption, while a negative $\Delta H°$ confirms an exothermic interaction, suggesting strong adsorption of inhibitor molecules onto the steel surface. Positive $\Delta S°$ implies increased disorder at the metal-solution interface due to inhibitor adsorption. These analyses are critical for determining whether physisorption or chemisorption dominates and for predicting inhibitor stability under varying operational conditions (Zarrok *et al.,* 2012; Zarrouk *et al.,* 2012; Husaini *et al.,* 2023; Kang *et al.,* 2025).

7. Computational and Modeling Studies

7.1 Density Functional Theory (DFT)

Density Functional Theory (DFT) is widely employed to investigate the electronic structure and reactivity of modified cellulose derivatives used as corrosion inhibitors. Through DFT calculations, key quantum chemical descriptors such as the highest occupied molecular orbital (HOMO), lowest unoccupied molecular orbital (LUMO), energy gap (ΔE), electronegativity, hardness, and softness can be obtained. These parameters allow prediction of the molecule's ability to donate or accept electrons, which directly influences its adsorption strength on the metal surface. A higher HOMO energy indicates greater electron-donating capability to the vacant d-orbitals of mild steel, enhancing chemisorption, while a lower LUMO energy facilitates back-donation from the metal, stabilizing the inhibitor-metal complex (Deng *et al.,* 2024; Li *et al.,* 2023). DFT is particularly useful for comparing different cellulose derivatives and guiding molecular design to improve inhibition performance (Alaoui *et al.,* 2025).

7.2 Molecular Dynamics (MD) Simulations

Molecular Dynamics (MD) simulations complement DFT by providing insights into the dynamic behavior of cellulose-based inhibitors on metal surfaces. MD allows the study of adsorption orientation, surface coverage, and interactions under realistic conditions such as varying temperature, solvent effects, and ionic environments. Functional groups like –OH, –COOH, and $–NH_2$ play a critical role in establishing hydrogen bonding or coordinate bonds with the steel surface, and MD simulations help visualize these interactions (Yousif *et al.,* 2025; Udunwa *et al.,* 2024). This approach also provides information on the stability and mobility of the inhibitor layer, which is essential for designing materials with long-lasting corrosion protection (Wang *et al.,* 2023).

7.3 Quantum Chemical Parameters

Quantum chemical calculations provide quantitative measures of inhibitor efficiency. Parameters such as dipole moment, global electrophilicity, nucleophilicity, and the fraction of electron transferred (ΔN) are determined to correlate molecular structure with inhibition performance. A larger ΔN value, for instance, indicates more efficient electron donation from the inhibitor to the metal, resulting in stronger adsorption and higher corrosion protection. These parameters also help in understanding the role of substituents or functional group modifications in enhancing inhibition efficiency and adsorption strength on mild steel surfaces (Zhang *et al.,* 2024a; Abdelhamid, 2024).

7.4 Correlation with Experimental Results

Computational studies are validated by correlating theoretical predictions with experimental findings, including electrochemical measurements, weight loss studies, and surface characterization techniques like SEM, AFM, and XPS. Agreement between experimental and computational data confirms the proposed inhibition mechanisms and provides confidence in the predictive capability of DFT and MD simulations (Zhang *et al.,* 2025; Li *et al.,* 2023). This integrated approach enables the rational design of advanced cellulose-based inhibitors that are optimized for acidic environments and industrial applications, minimizing trial-and-error experimentation (Alaoui *et al.,* 2025; Yousif *et al.,* 2025).

8. Applications in Industrial Systems

8.1 Acid Pickling Processes

Acid pickling is a critical step in many industrial applications, where steel surfaces are treated with strong acids such as hydrochloric or sulfuric acid to remove rust, mill scale, and other surface oxides. This process is essential to prepare the steel for further manufacturing, coating, or welding operations. However, during pickling, the metal is exposed to highly corrosive conditions that can rapidly degrade

its surface, reducing its structural integrity. Modified cellulose-based inhibitors provide a sustainable and eco-friendly solution by adsorbing onto the steel surface and forming a protective barrier (Khamis *et al.,* 2025). The abundant hydroxyl, carboxyl, and amine groups in cellulose derivatives facilitate strong chemical interactions with the metal, creating a stable film that minimizes metal dissolution (Singh *et al.,* 2025). The use of cellulose-based inhibitors not only improves corrosion resistance but also reduces reliance on conventional toxic chemicals, thereby lowering environmental impact and enhancing workplace safety (Nejad Keivani and Mohammadi, 2025). The adaptability of cellulose allows for the development of derivatives with tailored functional groups to optimize performance in different acid concentrations and temperatures (Peter *et al.,* 2025).

8.2 Oil and Gas Acidizing Operations

In oil and gas industries, acidizing is used to enhance hydrocarbon production by dissolving carbonate and silicate formations surrounding the wellbore. Mild steel components such as tubing, casings, and downhole tools are continuously exposed to highly aggressive acidic environments under extreme pressure and temperature. These conditions accelerate corrosion, resulting in equipment failure, operational delays, and significant economic loss. Modified cellulose-based inhibitors offer a promising green alternative by forming a protective adsorbed layer on steel surfaces, effectively reducing the rate of acid attack (Kumar and Das, 2023). Functional groups in cellulose, such as –OH, –COOH, and $–NH_2$, interact with metal surfaces via hydrogen bonding, coordinate bonding, and electrostatic interactions, providing a durable and efficient barrier (Aldahiri *et al.,* 2025). Additionally, the chemical tunability of cellulose enables the design of inhibitors that remain stable under high temperatures and pressures, conditions common in oilfield operations (Răuță, 2025). Incorporating cellulose-based inhibitors into acidizing fluids not only extends equipment lifetime but also reduces environmental hazards associated with conventional synthetic inhibitors (Elayachy *et al.,* 2025).

8.3 Cleaning and Descaling Processes

Cleaning and descaling operations are performed in various industrial facilities to remove scale, mineral deposits, and corrosion products from steel surfaces. These processes often use acidic solutions that can aggressively attack metals, making corrosion protection a significant concern. Conventional inhibitors, though effective, may produce toxic by-products and require careful handling and disposal. Cellulose-based inhibitors provide an environmentally friendly alternative, offering high efficiency and biodegradability (Alhaidar, 2024). The adsorption of cellulose derivatives onto steel surfaces forms a continuous protective layer, which minimizes metal loss while allowing acids to efficiently remove unwanted deposits (Khamis *et al.,* 2025). Furthermore, the chemical versatility of cellulose enables the development of inhibitors with enhanced film-forming ability, thermal stability,

and compatibility with other treatment chemicals (Singh *et al.,* 2025). This ensures that protective performance is maintained even under prolonged exposure, making cellulose-based inhibitors suitable for repeated cleaning cycles or continuous industrial operations (Nejad Keivani and Mohammadi, 2025). The use of such green inhibitors supports sustainable manufacturing practices while safeguarding metal integrity (Peter *et al.,* 2025).

Conclusion

Cellulose-based materials represent a promising class of eco-friendly corrosion inhibitors for mild steel in acidic environments due to their abundance, biodegradability, and chemical tunability. Chemical, physical, and nanostructured modifications significantly enhance their adsorption ability, film formation, and overall inhibition efficiency. Experimental techniques such as weight loss measurements, electrochemical methods, surface characterization, and thermodynamic/kinetic analyses, complemented by computational studies, provide a comprehensive understanding of their performance and mechanisms. Despite the promising results, challenges, including stability in harsh acidic conditions, high modification costs, reproducibility issues, and limited long-term performance data, must be addressed to ensure practical industrial application. Ongoing research focusing on standardized methodologies, scalable green modifications, and long-term evaluation will be critical to establishing cellulose-based inhibitors as viable, sustainable alternatives to conventional synthetic inhibitors.

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