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Sour Service Without Greenwashing: Palm-Fatty-Acid Imidazolines, Persistent Corrosion Films and Evidence-Based Pipeline Integrity in CO2/H2S Systems

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ABSTRACT

Wet oil-and-gas pipelines exposed to carbon dioxide (CO2), hydrogen sulphide (H2S), produced water and fluctuating operating conditions require dependable control of both generalised corrosion and localised integrity threats. Palm-derived fatty acids are chemically plausible precursors for nitrogen-bearing imidazolines and amidoamines, but renewable provenance alone does not establish corrosion inhibition, film persistence or environmental superiority. This critical qualitative literature review interprets recent corrosion, oleochemical, surface-science and sustainability evidence without claiming exhaustive systematic retrieval. The synthesis distinguishes direct palm-based evidence from non-palm molecular analogues and separates initial electrochemical efficiency from pitting resistance, under-deposit access, dynamic washout, top-of-line exposure and hydrogen-related service limitations. Mechanistic findings identify variable roles for head-group chemistry, hydrophobic-tail structure, protonation, micellization, hydrolysis, corrosion products and phase partitioning in governing apparent efficacy. A six-gate Palm-Derived Corrosion Inhibitor Qualification Framework is proposed, progressing from feedstock verification and molecular characterization through controlled bench, deposition, dynamic-flow and monitored field evidence, with environmental and safety checks at each level. The key recommendation is conditional development: chemically reproducible palm-based candidates merit comparative study, but no broad claim of sour-service pipeline integrity or green superiority is justified without application-specific testing, localized-damage monitoring and whole-formulation environmental assessment.

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Introduction

Internal Corrosion and the Operational Meaning of Sour Service Carbon-steel gathering lines and transport equipment operate in chemically and mechanically variable conditions. Dissolved carbon dioxide contributes to an aqueous carbonate system capable of sustaining metal dissolution, while hydrogen sulfide can alter reaction paths, iron-sulfide deposits and hydrogen entry. The designation sour service is therefore more than a label for a particular gas composition: water availability, gas partial pressures, temperature, pH, chloride activity, corrosion-product history and the mechanical requirements of the steel all determine the integrity challenge. Production changes may move a line between water-lean and water-wet states or convert relatively steady conditions into intermittent exposure. A credible corrosion-control strategy must start with these coupled service variables, rather than benchmark a new additive in a convenient but incomplete electrolyte [1-4].

The distinction between uniform and localised deterioration is particularly important. Mean thickness loss estimated from a coupon or linear polarisation measurement can look acceptable while a small population of pits continues to deepen. Corrosion beneath deposits may be even harder to detect because the scale changes mass transport and local chemistry. Moreover, H2S can participate in hydrogen absorption phenomena and service-specific cracking susceptibility; reducing a measured electrochemical metal-loss rate is not itself a certificate against hydrogen-induced cracking or sulfide stress cracking. Qualification must therefore include material-specific and failure-mode-specific considerations, calibrated to actual duty rather than an assumed universal inhibitor efficiency [5-7].

Why Renewable Fatty-Acid Inhibitors Deserve Conditional Investigation

Fatty-acid-derived imidazolines are plausible surface-active corrosion inhibitors because a nitrogen-containing molecular region can interact with a metallic or corrosion-product surface while a hydrophobic chain changes the local water-access barrier. Palm mesocarp oil and palm-kernel oil present different distributions of chain length, unsaturation and minor constituents. These chemical differences can help researchers assemble testable structure–performance libraries rather than treat palm as one uniform chemical. Importantly, the oil extracted from a fruit, a methyl ester produced from its fatty acid, an amidoamine intermediate and a cyclized imidazoline are distinct chemical substances. The existence of a low-cost agricultural supply does not eliminate the need to identify the synthesized active molecule, impurity fractions and final delivery solvent [8-11].

This review is motivated by a common translational problem: many studies report impressive inhibition efficiencies from short electrochemical tests, but industrial performance depends on whether the active molecules arrive at wetted steel, assemble into a resistant film, survive rewetting and flow disturbances, and remain useful after chemical aging. Such concerns are no less important for a renewable formulation than for a conventional one. Direct recent evidence on fatty-acid imidazolines includes work using tall-oil fatty acids, waste cooking oil and selected other biological feedstocks, which demonstrates chemistry and limited-test feasibility. These studies are informative analogues, not direct demonstrations that a particular palm-derived product has passed a production-pipeline acceptance test [12-15].

Research Problem, Scope and Analytical Contribution

The core research question is not whether an imidazoline can inhibit carbon-steel corrosion under any laboratory condition. It is which molecular and operational evidence is needed before a palm-origin candidate could be recommended for a defined CO2/H2S-containing production or transport system. The article brings together organic synthesis, molecular adsorption, multiphase corrosion, pitting, under-deposit effects and environmental assessment. It treats a candidate as a specified mixture applied to a specified steel, fluid and operating envelope. This decision-based unit of analysis prevents broad generalizations from a selected result at one dose, temperature or brine composition. The proposed original contribution is an explicit six-gate qualification framework in which negative results guide redesign or rejection and cannot be averaged away by attractive short-term efficiencies [16-19].

Three boundaries govern interpretation. First, sources based on sunflower, tall-oil, glucose, waste cooking oil or idesia oil support analogies about molecular motifs but cannot prove the performance of an untested palm analogue. Second, studies in hydrochloric-acid cleaning solutions or drilling fluids cannot automatically be transferred to produced-water conditions because exposure chemistry, wetted surfaces, flow and process requirements differ. Third, a favorable inhibition percentage is an experimental measurement, not evidence of improved remaining life, lower failure probability or net environmental benefit without further data. These boundaries retain the scientific value of adjacent literature while resisting overstated claims about industrial readiness [20-23].

Literature Review: Chemical, Corrosion and Integrity Foundations

CO2/H2S Electrochemistry and Corrosion-Product Interfaces

Dissolved CO2 contributes acidic species and influences cathodic reactions and ferrous carbonate precipitation, whereas H2S introduces sulfide species and iron sulfide phases with different kinetic and transport consequences. The relative action of these species depends on partial pressures, pH, dissolved salts and temperature. Iron carbonate scales may provide partial protection under some conditions but can also create heterogeneous surface coverage and crevice-like electrolyte pockets. A sulfide-rich film is not necessarily protective simply because it appears visually continuous. Under some combinations of water chemistry and flow, sulfide can inhibit formation of more protective carbonate crystals or promote a porous scale through which aggressive ions still travel [24].

Flow introduces two competing effects. Transport can increase the availability of reactants to the steel while also distributing treatment chemicals more widely; shear may help mixing but can disturb weak corrosion products or adsorbed films. The effect is conditional on hydrodynamic regime and the chemical form of the surface layer. For this reason, a rotating-cylinder electrode or flow-loop observation should be interpreted within its actual Reynolds and shear conditions rather than being described as a universal simulation of a long pipeline. The presence of emulsified hydrocarbon, high water cut, solids and local wetting intermittency can further change both film delivery and corrosion behavior [25-26].

Recent pipeline experiments show why controlled hydrodynamic testing belongs in inhibitor qualification. Wen and colleagues combined electrochemical tests, autoclave exposures and multiphase flow-loop investigation of X65 steel, reporting flow-dependent corrosion and an imidazoline-based treatment result within a bounded operating envelope. This is more service-oriented evidence than a short static coupon experiment, but the findings still cannot establish qualification for a different inhibitor, steel, liquid holdup or H2S partial pressure. Reported wall shear, temperature, chemistry and exposure duration should therefore accompany every transfer claim [27].

Molecular Structure: Nitrogen Anchors, Fatty Tails and Phase Partitioning

An imidazoline ring and related amino substituents provide nitrogen-bearing sites that may coordinate with surface atoms or interact electrostatically with charged regions and corrosion products. Hydrophobic fatty chains can help impede the approach of the electrolyte when they assemble with sufficient coverage and suitable orientation. A single molecular sketch, however, gives little information about active concentration, protonation state, aggregation, hydrolysis products or the oil-water distribution of the inhibitor. Chain length, branching, saturation and polar co-functional groups determine behavior collectively. An optimum observed in a homologous series may reflect a balance of solubility, adsorption and molecular packing rather than a simple principle that longer is always stronger [28].

Independent molecular-engineering studies expand the range of testable imidazoline architectures. Peng and colleagues modified oleic imidazoline with sulfur-bearing functionality for a supercritical-CO2 system, whereas Li and colleagues introduced thiourea- and phosphine-containing units into a laurate-imidazoline structure for combined scale and corrosion screening. Neither precursor origin nor a high inhibition figure identifies the optimum molecule for a wet gathering line, because these studies concern specific pressure, phase, temperature and fluid conditions. Together they justify matched head-group experiments that separate the roles of surface anchoring, scale interactions and aqueous availability [29-30]

Work on thiophene-imidazoline series demonstrates that structurally related derivatives can show different efficiencies under similar CO2-saturated produced-water conditions. Other studies show that imidazoline adsorption can be strong in simple saline solutions yet change when surface deposits, steel composition or pretreatment differ. Modelling approaches such as density-functional theory and molecular dynamics can propose electron-density and adsorption configurations; their predictions remain dependent on represented surface chemistry and solvent conditions. When comparing candidate palm-derived molecules, it is more convincing to study matched analogues with controlled head groups, side chains, molecular concentration and solution chemistry than to infer active performance from a fatty-acP_{ij},$\vec{a}_{1n}$ce label [31].

Micellization, Protonation, Hydrolysis and Concentration Effects Imidazoline systems can behave as surfactants whose molecules redistribute among bulk water, oil, micelles and the steel interface. Acid-base state changes dispersibility and adsorption, while aggregation above a critical micelle concentration can change the amount of monomeric material available for surface replenishment. Hydrolysis and reactions during hot, acidic storage may convert a target imidazoline into other compounds whose film-forming behavior differs. Consequently, nominal injected concentration is not identical to the active concentration arriving at the surface after residence in a pipeline. Analytical tracking of the actual active component and products of aging is necessary before claims of long-lived protection are justified.

Time dependence creates a methodological trap. A promising inhibitor may lower corrosion current soon after injection, but the measured efficiency can decrease as adsorption competition, water-wetting changes, or chemical conversion alters film coverage. Conversely, a corrosion-product layer may provide independent protection that is incorrectly credited entirely to the additive. Some experiments demonstrate materially different outcomes after deliberate pre-corrosion, and inhibition of a previously damaged surface can require different conditions from prevention on freshly polished steel. Comparative studies should therefore measure initial adsorption, sustained corrosion behavior, film loss after inhibitor withdrawal and recovery after redosing, with explicit records of the evolving surface.

The Limits of Standardized Electrochemical Indicators

Linear polarization resistance, electrochemical impedance spectroscopy, potentiodynamic polarization and gravimetric loss offer complementary information, but no single test directly measures all forms of damage. Electrochemical monitoring can sensitively indicate a changing interface, whereas long-duration coupons provide integrated mass loss and surface profilometry can identify pits. Equivalent-circuit interpretation of impedance data depends on assumptions about resistive and capacitive features, which should be justified rather than presented as direct photographs of a molecular film. Agreement among independent methods increases confidence, yet consistency must be assessed under matched conditioning and with replicated samples. The minimum evidence package should contain untreated controls, solvent-carrier controls, a commercial benchmark and uncertainty estimates [32-33].

Inhibition efficiency (IE) may be defined as the proportional reduction in measured corrosion rate (CR) relative to a contemporaneous untreated control. When both corrosion rates are determined using the same method and the untreated rate is positive, $IE\ (\%) = [(CR_0 - CR_i) / CR_0] \times 100$, where CR_0 is the untreated rate and CR_i is the treated rate. This numerical definition is useful for standardised comparisons but is sensitive to a small untreated denominator, test time and changes in the inferred electrochemical rate. Reporting 95% inhibition without the baseline corrosion rate, test duration, experimental variability and surface morphology can conceal operationally important residual damage. It is equally inappropriate to use a single point-in-time efficiency as a forecast of cumulative wall loss. The better practice is to plot treated and untreated corrosion rates through time and to report the final coupon mass change and distribution of pit depths separately [34].

Borko and colleagues provided another useful contrast by assessing oleic-acid imidazoline both alone and in combination with a cerium salt in CO2-saturated brine. Their study is relevant to formulation design because mixture performance may reflect changes in surface film chemistry as well as the behaviour of the organic inhibitor. It also warns against attributing a formulation result solely to the fatty-acid tail when a co-additive is present. Such comparisons should report both separate components and their mixture over the same time interval and steel surface history [35].

Under-Deposit Corrosion and Wetting Heterogeneity

Deposits of CaCO3, sand, sulfide, iron carbonate and organic material may obstruct the transport of active inhibitor molecules to steel. The influence of a deposit is not described by its chemical name alone: thickness, porosity, pore-connectivity, bonding to the surface and local flow are consequential. Experimental evidence on imidazoline penetration through scale makes clear that a molecule may need both adequate permeation and intrinsic inhibitory power to protect beneath a deposit. Other comparisons reveal that water-soluble derivatives can outperform oil-soluble imidazoline analogues in selected deposit geometries. Hence, high inhibition against uncovered steel cannot be extrapolated to a buried contact without a dedicated penetration test [36-38].

The timing of injection matters as well. In some under-deposit experiments, inhibitor introduced after prior corrosion provided less protection than inhibitor added before damage developed. Such behavior may arise from restricted access, different corrosion-product morphology or adsorption on surfaces already altered by localized attack. Oxygen ingress, even brief, can change existing carbonate films and produce localized conditions that persist beneath deposits. For asset management, these observations support preventive dosing and systematic cleanliness where appropriate, while also warning that chemistry alone may not restore a degraded surface. Trials should compare clean, pre-corroded and deliberately deposit-covered steel with measured deposition geometry, rather than only repeat polished-coupon tests.

Top- and Bottom-of-Line Corrosion, Sulfide and Mechanical Integrity

Top-of-line and bottom-of-line exposure present distinct transport and wetting problems. Bottom-of-line steel may contact persistent brine, while the upper wall can experience transient condensation droplets whose supply of inhibitor depends on volatility, entrainment or aerosol transport. Recent studies demonstrate that some azoles and fatty-acid imidazolines can inhibit both positions in simulated systems, but results are formulation-, condensate- and temperature-specific. In one study, protection at the top was attributed to droplet-carried material rather than straightforward gaseous vapor transport. Therefore the term volatile corrosion inhibitor should not be accepted as proof of vapor-phase delivery without appropriate analytical evidence of the transport mechanism [39,40].

H2S creates another independent dimension because iron-sulfide films, sulfur chemistry and hydrogen entry can change the outcome relative to CO2-only tests. Certain inhibitor classes lose effectiveness in mixed-gas brines even when they perform adequately under sweet conditions, whereas positively charged compounds can respond differently. The safety implications are larger than uniform corrosion because sour service may involve hydrogen-related cracking risks governed by metallurgical susceptibility, loading and environmental severity. Selection of qualified pipe materials, welding controls, inspection planning and service-specific integrity assessment remain essential. Chemical inhibitor experiments should therefore be framed as metal-loss and localized-corrosion control tests unless separate evidence

explicitly addresses cracking susceptibility [41].

Method: Critical Qualitative Literature Review

Review Design and Source Boundaries

This study uses a qualitative literature review with a critical interpretive design. It is not a systematic literature review, network meta-analysis or bibliometric census. Literature published from 2020 through 2026 was selected for relevance to oil-and-gas corrosion, imidazoline and fatty-acid chemistry, adsorption, wetting, under-deposit corrosion, local attack, sustainability and pipeline integrity. Purposive sampling deliberately included high-performance reports alongside evidence that limits the implications of early success. The review does not calculate pooled inhibition efficiency because results differ in inhibitor chemistry, metal surface, brine, partial pressures, temperature, dosing and exposure time. A single synthetic average from these heterogeneous studies would obscure rather than resolve field applicability.

The sources were divided into four substantive categories. The first includes chemically characterized fatty-acid imidazoline experiments in relevant corrosive media; the second comprises oleochemical and adjacent vegetable-oil syntheses with transferable but indirect design lessons; the third addresses CO2/H2S corrosion, deposit formation, surface damage and operational limits independently of additive feedstock; and the fourth concerns lifecycle analysis, palm-oil governance and environmental claims. No source is allowed to migrate automatically from one category to another. In particular, the absence of readily verified, long-duration field-pilot evidence for a specific palm-derived inhibitor is reported as a gap in this reviewed material, not as proof that such data cannot exist privately.

Cross-Disciplinary Coding and Counterevidence

First-cycle conceptual coding distinguished molecular precursor, conversion chemistry, active identity, aqueous or hydrocarbon partition, electrochemical response, surface morphology, time dependence, fluid regime, deposit accessibility and environmental burden. A second cycle grouped these variables into themes of molecular design, interface formation, film durability, local corrosion, sour-service transfer, laboratory-to-field qualification and lifecycle integrity. Direct experimental observations were distinguished from computational mechanisms and broader industrial inference. A paper demonstrating high adsorption energy or attractive molecular alignment in a simulation was treated as a hypothesis supporting experimental design, not as measured pipeline reliability.

Negative cases were essential to the synthesis. Reports of hydrolysis, surface-dependent adsorption, reduced performance after pre-corrosion, pitting despite low mean rates, limitations beneath deposits and mixed-gas interactions were retained rather than discarded in favor of high reported efficiencies. These examples reveal the conditions most likely to invalidate an optimistic interpretation. This approach does not assign a formal systematic-review risk-of-bias score, but it makes the evidentiary distinctions explicit: study conditions, controls, uncertainty, relevant damage endpoints and independent replication determine the reach of a claim. The resulting readiness framework is a normative engineering proposal derived from cross-study interpretation, not an independently validated international standard.

Limits of Inference and Citation Scope

Several limitations remain. Some peer-reviewed corrosion articles are performed in simple acid solutions, on steel grades not used in a particular pipeline, or under brief exposures. These works can inform molecular design but do not establish validity for mixed CO2/H2S transport. Environmental research on palm land conversion illuminate's feedstock sourcing risk but does not calculate the lifecycle footprint of a specific additive without measured yield, dose and manufacturing inputs. The literature also includes field-specific information that is often proprietary, creating an unavoidable asymmetry between visible laboratory results and industrial experience. Conclusions are consequently conditional and confined to the evidence examined, with specific gaps identified for controlled field-facing tests [42-44].

Results: Thematic Synthesis

Theme I- Fatty Acid Feedstock is a Design Input, Not a Finished Inhibitor

Palm fatty-acid portfolios can support distinct molecular design routes because mesocarp and kernel fractions differ in chain length, saturation and related processing requirements. In contrast to a claim that a natural triglyceride is a corrosion inhibitor, this approach begins with fatty-acid identity and finishes with a verified imidazoline or amidoamine product. Synthesis can involve condensation with polyamines, removal of water and conversion through intermediate amides, followed when necessary by further quaternization or chemical modification. Each step can alter protonation, impurities, solubility, biodegradability and manufacturing energy demand. Adequate structural verification must precede performance interpretation; a finished formulation should report its active fraction, residual amines, fatty-tail distribution, carrier and stability in storage.

The evidence establishes feasibility for oleochemical imidazolines from several feedstocks but offers no license to treat them as equivalent. A tall-oil-derived molecule with a similar alkyl chain can suggest a rational target for a palm olein stream, and a waste-cooking-oil derivative can demonstrate manufacturing potential under a different source mix. However, double-bond distribution and impurities may vary, while the chosen head group and final chemical structure can dominate adsorption behavior. Controlled palm-specific synthesis should therefore compare characterized C12, C16, saturated C18 and unsaturated C18-derived derivatives against structurally matched non-palm controls. Such studies would identify the causal contribution of fatty-tail composition rather than publish an uncontrolled comparison of feedstock labels.

Figure 1 summarizes the design chain identified in this thematic synthesis. It begins with a measurable precursor, progresses through defined chemical conversion and molecular architecture, and ends with a set of service-relevant performance gates. This separation matters because each arrow represents a research proposition to test rather than a guarantee of successful performance. Renewable supply creates molecular opportunity, but reliable protection depends on the active compound, steel condition and corrosive exposure together.

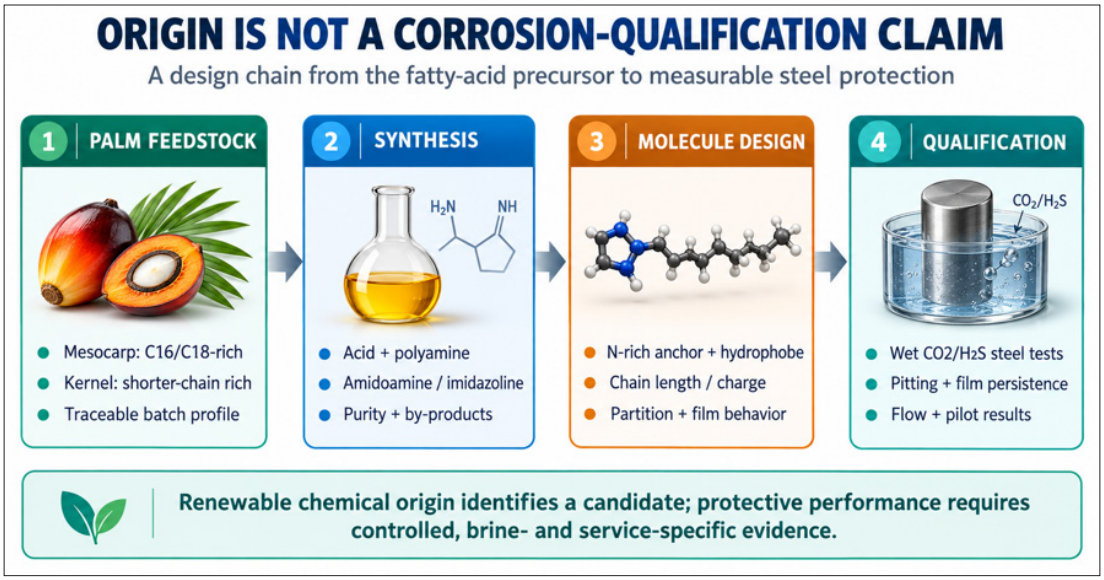


Figure 1: A Traceable Palm-Based Fatty-Acid Precursor Requires Conversion, Molecular Identification And Brine- and Service Specific Qualification Before any Service Claim is Justified

As illustrated by Figure 1, a feedstock-quality check is not interchangeable with a molecular-identity check, and neither replaces corrosion testing. The sequence recommends analytical checks at each stage: chromatography for fatty-acid distributions, spectroscopy and relevant mass analysis for conversion, and independent confirmation of residual species or solvents. Product development should treat unsuccessful comparisons as information about structural mismatches, because such outcomes help distinguish low adsorption from insufficient solubility or chemical degradation. This staged logic reduces the likelihood that a promising environmental story gets ahead of the underlying materials science.

Theme II - Initial Adsorption and Persistent Films are Different Outcomes

A recurring observation across imidazoline work is that strong early protection can coexist with sensitivity to aging, steel pretreatment and solution conditions. The adsorption-active head group may initially occupy accessible surface sites, but sustained performance depends on transport of replacement molecules and retention of the film during flow, salt exposure or intermittent water wetting. Hydrolysis studies show that fresh and pre-aged imidazoline formulations can influence uniform and localized corrosion differently. Likewise, research on steel containing varying copper and carbon-related surface phases shows that metallic microstructure can influence adsorption kinetics. These results argue against ranking candidate molecules only by an initial impedance spectrum or a best-case calculated surface coverage.

A further question concerns the interaction between organic protective films and inorganic surface treatments. A 2025 study of bioderived imidazole derivatives combined with zinc ions illustrates that multicomponent adsorption and synergistic effects can influence initial corrosion measurements. However, the reported combination does not directly demonstrate a persistent fatty-acid imidazoline film after injection stops or that a palm precursor is superior. The next experimental step should therefore include matched single-agent controls, timed washout, independent measurement of metal dissolution and surface morphology, and chemical analysis of the residual film.

An operationally relevant film-persistence experiment should precondition specimens in representative brine, establish a known inhibitor dose, and then subject them to flow and chemical withdrawal or dilution. Time-resolved electrochemistry can be paired with surface analysis, continuous monitoring of active concentration and redosing at predetermined intervals. The response should include whether a film disappears rapidly after treatment stops, whether corrosion accelerates locally and whether the surface can recover after renewed injection. A durable inhibitor is not defined by permanent adhesion; it is defined by delivering controlled corrosion risk under realistic supply and disturbance patterns. These tests are especially useful when a pipeline experiences injection outages, changing flow, shutdown and restarting.

Theme III — Mixed-Gas Performance Must Be Measured Rather Than Inferred

Comparative studies in CO2-only and CO2/H2S environments indicate that inhibitor rankings can depend on the sulfide component. The molecular charge of the inhibitor, nature of reactive sulfur species and evolving iron sulfide layer can collectively shift adsorption. The absence of H2S in a test is therefore an important limitation, even when the bulk temperature and ionic strength resemble the intended field. A qualification matrix should test several gas ratios, gas partial pressures and periods of exposure, while recognizing that H2S hazards require suitable containment and specialist facilities. CO2-only results are useful as a reference condition but should never be used as the only basis for approving treatment of a sour line.

Studies of high-pressure CO2 transport further illustrate that corrosive species interact rather than act as interchangeable background impurities. Ding and colleagues assessed the importance of water content and several impurities for X52 steel and separately developed a mechanistic framework for CO2–H2S–chloride conditions, while Yang and colleagues examined combined H2S and SO2 effects on X65 corrosion products. These results concern largely CO2-transport contexts and bare-steel mechanisms, not palm-derived inhibitors in petroleum-gathering brine. Their appropriate contribution here is to strengthen the case for chemically explicit sour-service test envelopes rather than to

import their quantitative corrosion rates directly [45-47].

Dynamic flow makes this issue more complex because the film-forming molecule and the corrosion-product layer respond to hydrodynamic forces differently. Increasing velocity might renew inhibitor supply but could also create mechanical loss of a fragile barrier or intensify local mass transfer through scale porosity. Sour-service tests should report the observed corrosion products and not simply infer them from gas composition. Sampling after a controlled exposure can help distinguish adsorption to bare steel from inhibition mediated by a carbonate or sulfide layer, a distinction critical for explaining why an apparently useful formula fails on a field-precorroded surface.

Theme IV - Average Inhibition Percentages Can Conceal Integrity-Relevant Failure

The most serious epistemic error in corrosion qualification is to treat a single mean inhibition percentage as a measure of pipeline integrity. Studies of local corrosion show that an effective dose for reducing average metal loss can be insufficient to suppress pits. Under a porous CaCO3 or heterogeneous iron carbonate deposit, aggressive solution can persist where inhibitor access is limited, even as a broad exposed steel region appears protected. The appropriate results therefore include maximum and statistical pit depth, pit density, cross-sectional deposit examination and corrosion rate through time. A damage-focused protocol should specify how pits are located, whether cleaning alters their geometry and how uncertainty is estimated from replicate specimens.

Evidence on inhibition beneath deposits continues to develop. Gai and colleagues examined imidazoline derivatives and thiourea beneath simulated inert deposits on X65 steel in CO2-saturated produced water, complementing the permeation-focused analysis of Fan and the delayed-injection observations of Jiang. Taken together, these studies strengthen the argument that dose selection for a clean surface does not adequately bound the risk of a shielded pit. Deposit geometry, penetration, dose history and local damage should be reported separately, particularly when the inhibitor must function in an existing and partially scaled production asset [48].

Top-of-line condensation and under-deposit geometries add two distinct variants of this problem. A chemical mixed into the flowing aqueous phase may protect bottom-of-line coupons but fail to reach intermittent droplets on the upper wall. Similarly, an inhibitor with excellent intrinsic adsorption may be unable to penetrate a dense deposit or may arrive only after a deep pit has developed. Film performance must therefore be evaluated at both exposure locations and under conditions that reproduce the specific failure mechanism. The review also identifies the need to avoid implying that localized metal loss and hydrogen-assisted cracking are interchangeable: the latter involves the mechanical condition and material susceptibility of the steel as well as the fluid chemistry.

Figure 2 organizes the six principal failure modes that should accompany a bench screening campaign. The first two distinguish general and localized metal loss; the third isolates film persistence; the fourth tests transport through deposits; the fifth demands separate sweet and sour conditions; and the sixth incorporates material and mechanical integrity. This analytical structure helps avoid the false assumption that a candidate passing one class of evidence automatically passes all others. In a deployment decision, a failed critical mode cannot be offset by a higher percent inhibition in a simpler test.

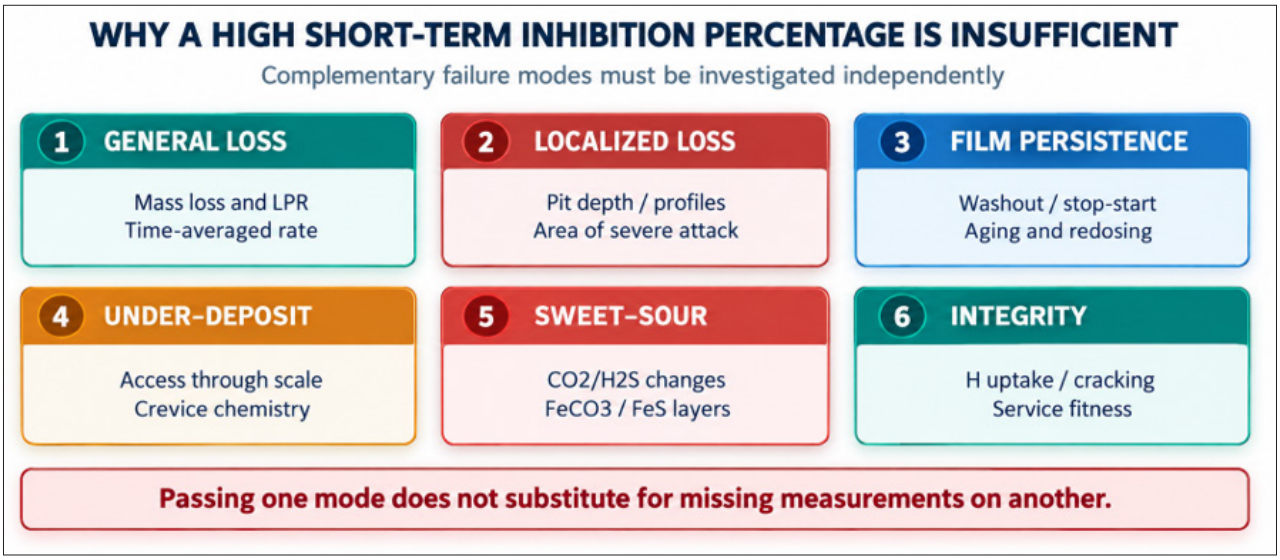


Figure 2: Six Independent Dimensions of Corrosion Control Evidence that Cannot be Reduced to a Single Laboratory Inhibition Percentage

Reading Figure 2 from general metal loss toward integrity highlights a progression from more accessible measurements to demanding failure modes. The sequence is not a claim that every system has equal susceptibility to all six hazards; rather, it is a screening tool requiring the operator to justify which hazards are material for the specific line. An acceptable result for a carbon-steel gas gathering pipeline with mixed condensate and sulfides may need different weighting from an oil-dominated low-water-cut service. Transparent hazard-based justification is preferable to a universal numerical pass mark that lacks scientific validation.

Theme V - Environmental Performance is a Separate Empirical Hypothesis

Renewable origin can provide a useful starting point for material substitution, but it does not determine complete-formulation

biodegradability or toxicity. An imidazoline may contain bio-based carbon while incorporating synthetic reagents, persistent heterocycles, a fossil-based solvent package or other constituents that influence environmental fate. Some modern vegetable-oil-derived inhibitors have reported encouraging biodegradability measurements, yet those results are attached to the tested molecules, conditions and assay definitions. They do not automatically describe a new palm-derived analogue. Any claim of aquatic safety requires direct testing of the final formulation at relevant environmental concentrations rather than inference from the feedstock's agricultural origin.

Palm sourcing introduces another set of independent trade-offs. Land conversion, biodiversity, carbon-rich forests, certification, yield improvements and livelihoods have all been studied at scales far removed from the steel interface. They matter when a product is called sustainable, because the origin of the fatty-acid fraction and the counterfactual alternative can change the direction of an environmental comparison. Palm's relatively high oil yield per unit area can coexist with severe environmental costs when expansion affects sensitive habitats. The proper analytical question is therefore whether a qualified palm formulation, at its actual treatment dose and production yield, offers a better lifecycle profile than its relevant conventional or waste-derived comparator under a consistent functional unit [49,50].

The practical functional unit for an industrial comparison should relate chemical manufacturing, transport and treatment to a measurable protection service: for example, a defined volume of fluid transported while meeting specified corrosion and inspection objectives over a stated time. Assessments could include source certification, conversion energy, reagent consumption, solvent recovery, packaging, injection infrastructure, aquatic release and costs of maintenance interventions. Direct operational savings should be quantified rather than guessed. If the formulation has no convincing corrosion benefit, a lower estimated feedstock carbon intensity is insufficient to justify deployment as an inhibitor. In this sense, environmental assessment is an independent qualification gate with the possibility of a negative decision [51-53].

Discussion and Critical Analysis

A Coupled Molecular Surface Service Interpretation

The evidence can be synthesized through three necessary and interacting explanations: molecular identity determines possible adsorption behavior, the condition of the steel and its corrosion products controls whether an accessible protective interface exists, and operations determine how long that interface survives. A useful palm-derived molecule may therefore fail because of poor solubility even when its adsorption geometry is attractive, because mineral scale excludes it from a pit, or because its protective film does not survive intermittent water wetting. These are different mechanistic failures requiring different redesign choices. The value of a critical review is to identify these alternatives before investigators declare that a molecule with a renewable tail is universally effective.

This approach also clarifies the role of computational chemistry. Density-functional calculations and molecular dynamics can compare binding motifs, charge distributions and interaction energies, helping researchers prioritize molecules for synthesis. Yet these models often represent idealized surfaces and short timescales. They generally omit the complete changing assembly of carbonate scale, sulfide products, fluid shear, long-term hydrolysis, oxygen contamination and field dosing limitations. A model's strongest contribution is therefore to generate a falsifiable hypothesis and identify discriminating experiments. Inhibitor claims become more credible when model predictions, spectroscopy, interfacial analysis and long-duration corrosion results converge under the same operating assumptions.

Six-Gate Palm-Derived Corrosion Inhibitor Qualification Framework

A candidate should progress through six cumulative gates. Gate 0 verifies feedstock origin, fatty-acid distribution and traceability. Gate 1 verifies synthetic conversion, active molecular identity, impurities and realistic stability. Gate 2 tests the chemical under defined CO2-only and CO2/H2S environments using mass loss, electrochemical monitoring, replicate controls and localized surface analysis. Gate 3 adds real or reproduced mineral deposits, prior corrosion, top-of-line condensate and deliberate under-deposit accessibility tests. Gate 4 tests dynamic flow, washing, injection interruption, thermal cycling, phase changes and compatibility with companion chemicals. Gate 5 is a monitored service pilot with safety governance, corrosion-management targets and operational economics. The environmental gate operates at every level.

Progression between gates should depend on prespecified performance and evidence-quality thresholds. Minimum acceptable criteria must be calibrated to the operator's actual corrosion allowance, inspection intervals and severity of sour-service exposure, not invented as universally applicable fixed percentages. Failure can mean insufficient adsorption, a rapid loss of active component, a high residual pit-growth rate, unacceptable deposit penetration, antagonism with another injection chemical or adverse ecotoxicological findings. The framework intentionally rejects a weighted-average score that permits a severe localized-corrosion risk to disappear behind a favorable general corrosion rate. It instead adopts a weakest-critical-gate logic and requires documented technical justification for either advancing, redesigning or rejecting the candidate.

Figure 3 presents the proposed readiness framework as a decision tool. Its path is cumulative: earlier characterization remains relevant after subsequent testing because manufacturing changes may invalidate a previous qualification. The framework's environmental and safety band demonstrates that renewable origin is not a terminal prize awarded at field deployment; sourcing, biodegradation and hazard need attention from the initial concept onwards. The route is intended to guide research investment and testing rather than serve as a claim that any currently reviewed palm-based inhibitor has already reached Gate 5.

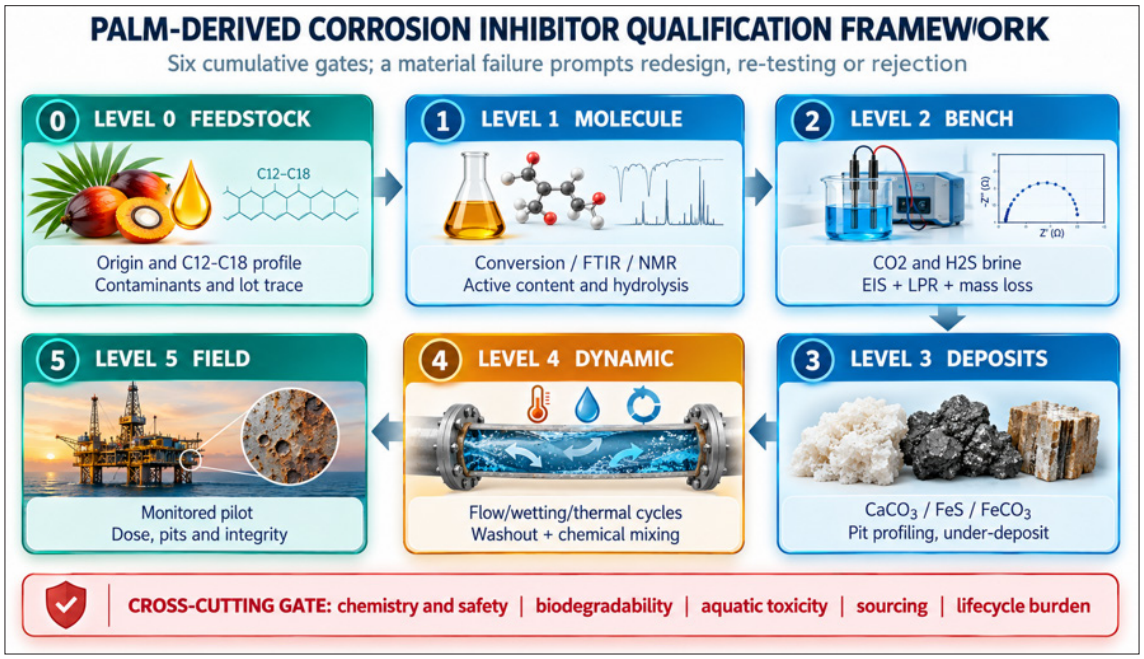


Figure 3: Six Cumulative Corrosion-Inhibitor Qualification Gates with Environmental and Safety Assessment Integrated at Every Level

Figure 3 also identifies practical evidence handoffs. The Gate 1 analytical report should travel with samples to the Gate 2 laboratory; the composition and measured active dose used in Gate 2 should be maintained or explicitly varied during Gate 3 deposit trials; and Gate 4 should reproduce the relevant injection and wetting pattern envisaged for Gate 5. If a new synthesis route alters the product's chain-length profile or residual reactive species, earlier assumptions must be retested. A stable data lineage makes qualification more rigorous and enables future research groups to identify why two apparently similar inhibitors yield contrasting outcomes.

Proposed Reporting Standard and Controlled Test Programmer

A publication intended to support industrial decisions should report a complete chemical description of the active ingredient, batch-to-batch reproducibility, dosed concentration on an active basis, carrier blank, brine composition, gas partial pressures, steel grade, surface finish and pre-corrosion history. Test reports should specify specimen geometry, thermal conditioning, flow or rotation regime, duration, replicate number and data quality. Corrosion outcomes should include untreated and commercial-inhibitor controls and should distinguish mean corrosion rate from localized pit morphology. Where electrochemical impedance spectra are used, the choice of circuit model and uncertainty of fitting should be disclosed; where simulation is used, surface and solvent assumptions should be explicit.

For molecular development, a controlled factorial experiment would compare fatty-chain composition and head-group design without allowing synthesis conditions to vary invisibly. At least one series should hold the polar head constant while varying C12, C16, C18:0 and C18:1 derived moieties; a second could hold the tail constant while comparing selected imidazoline, amidoamine and quaternized forms. Test several real produced waters and steels with contrasting scale conditions. The response variables should include active dissolution, adsorption kinetics, corrosion current, mass loss, pit depth, film retention after washout and under-deposit penetration. This programme would test the claim that molecular differences, rather than uncontrollable impurities, cause observed protection.

A full factorial study should also distinguish formulated mixtures from their nominal active molecules. In the 2025 study of oleic imidazoline and CeCl3, the mixture and individual components formed different experimental comparisons; the reported results should not be generalized to untreated sour conditions. The same logic applies to modern imidazoline derivatives developed for high-pressure CO2 or dual scale-and-corrosion control. Every additional functional component introduces a new source of efficacy, incompatibility and environmental burden that should be independently quantified.

Environmental experiments should be embedded alongside performance testing. Biodegradation studies must report the assay, duration, complete test material and interpreted threshold, while aquatic toxicity should address relevant species or validated screening procedures. Comparative lifecycle calculations require mass and energy inventories for synthesis, wastewater handling and final dosing rather than borrowing the carbon footprint of a different biofuel or lubricant product. The economic analysis should track chemical price, required dose, corrosion-management benefit, logistics, equipment downtime and risk-based maintenance. A candidate that is inexpensive by kilogram may be expensive per reliable treatment because of higher dose, instability or frequent injection interruptions [54].

Table 1 translates the qualification narrative into minimum evidence and critical failure indicators. It is not a universal acceptance specification: the numerical limits and test duration must be justified from each asset's risk assessment and should be set before candidate screening begins. The table explicitly prevents favourable general-corrosion results from concealing unresolved pitting, deposit or cracking hazards.

Domain / gate	Minimum evidence	Do not advance if...
Feedstock and synthesis	Fatty-acid profile; analytical identity; active content; impurity and carrier records	Identity, reproducibility or impurity risk is unresolved
Bench electrochemistry	Untreated, vehicle and benchmark controls; IE and absolute rates; time series; replicates	Rate advantage disappears or controls are inadequate
Localized and deposits	Pit-depth distribution; scale geometry; post-corrosion dosing; top-of-line tests as applicable	Local attack or inaccessible metal remains unacceptable
Film durability and dynamics	Flow and wetting cycles; washout; shutdown/ restart; redosing; compatibility	Film loss, washout or antagonism triggers unacceptable damage
Sour integrity	CO2/H2S chemistry; scale analysis; steel/ material susceptibility; integrity plan	Sour-service cracking/material requirements are unaddressed
Environmental and field	Full-formulation toxicity; biodegradation; traceability; pilot and service-normalized costs	Safety, field reliability or environmental case is unsupported

Table 1 should be interpreted as a hierarchy of non-substitutable evidence. For example, verified molecular purity cannot compensate for a rapidly growing local pit, while lower aquatic toxicity does not establish successful chemical delivery through scale. A monitored pilot is justified only after the material failure modes relevant to the line have been addressed with adequate controls and repeatability.

Comparing Chemical Treatment with System-Level Alternatives

Chemical inhibition is only one part of internal corrosion management. Water separation, control of liquid holdup, temperature and process conditions, pigging, deposit removal, choice of suitable materials, internal linings and inspection strategies can provide alternative or complementary protection. In a line with persistent solids accumulation, repeated inhibitor redesign may deliver less value than improving water and deposit management. In severe H2S duty, material selection and sour-service metallurgical qualification remain fundamental; an apparent reduction in mass loss cannot substitute for them. The framework therefore includes a comparator question at every stage: would the same operational objective be met more reliably or with a lower lifecycle burden by a different intervention?

The correct comparison should use risk and operational endpoints rather than chemical price alone. A continuously dosed inhibitor with high initial efficacy but uncertain survival during outage may impose a larger monitoring burden than a more expensive but resilient formulation or a non-chemical intervention. The cost of failure can include repair, environmental release, production interruption and injury, whereas economic gains from better corrosion control may include deferred replacement, fewer unplanned interventions and improved production availability. These quantities are site-specific and should be evaluated in a transparent decision model. The chemical with the highest reported percentage inhibition is not necessarily the option with the lowest total cost of integrity management.

A Critical Roadmap for Indonesia and Oleochemical-Producing Regions

Indonesia's oil-palm and refining infrastructure could support a research programme linking fatty-acid fractionators, polyamine chemistry, analytical laboratories and petroleum asset operators. An initial consortium could select traceable palm-oleochemical fractions and prepare a small number of fully characterized molecules with matched benchmarks. In the next stage, university and industry laboratories could test inhibition in representative produced waters and under contrasting CO2/H2S conditions using standardised coupons and electrochemistry. Only formulations that meet predetermined controls for uniform and localised corrosion should advance to deposit and dynamic testing. This sequence would create a meaningful experimental knowledge base before making investment or procurement decisions.

A subsequent demonstration programme should develop joint protocols for laboratory intercomparison and managed field observation. Operators should supply anonymized yet chemically useful ranges for brine, gas pressure, water cut, temperature, steel and existing treatment practice. Independent laboratories should verify the composition and stability of candidate batches; materials engineers should evaluate local corrosion and integrity hazards; environmental teams should review aquatic fate and sourcing documentation. Data ownership agreements should protect proprietary formulation details without making the basic service outcomes impossible to interpret. An independently observed negative result would be especially valuable because it would prevent repeated expenditure on chemical structures that fail for predictable reasons.

Sustainability governance should begin with sourcing choices, not merely with marketing descriptions attached to the finished inhibitor. Palm oil and palm-kernel oil have different downstream values, and using an established food-related stream for a specialty chemical may require explicit assessment of opportunity cost. Certified origin may strengthen traceability but does not automatically settle deforestation, land tenure or socioeconomic impacts. Research should compare high-performing palm-origin routes with alternatives based on waste cooking oil, other vegetable oils and existing commercial inhibitors, using the same operational function and actual conversion yield. The research agenda will be credible only if it accepts the possibility that the best choice may be a non-palm route or a non-chemical integrity solution.

Answering the Research Questions and Identifying Falsifiable Claims

The first two research questions can be answered with qualified optimism. Palm-origin fatty-acid chains provide chemically rational precursor possibilities, while recent literature supports the surface activity of nitrogen-bearing imidazolines and related derivatives. However, the best molecular structure cannot be selected from feedstock chain length alone because protonation, solubility, active concentration, tail packing and the corrosion-product interface influence behavior. The third and fourth questions yield more caution: CO2/H2S environments, prior corrosion, scale

and pitting can overturn conclusions inferred from simple aqueous tests. A convincing experiment should try to falsify favorable mechanisms by varying one structural property at a time and by retaining unfavorable material and exposure cases.

The evidence relevant to the fifth and sixth research questions shows why dynamic service qualification and localized integrity testing must remain explicit. A field pilot should monitor corrosion rates at several locations, active chemical delivery, changes in deposits, wetting conditions and local damage; it should also establish a baseline and safety response before injection begins. The review does not show that a palm-derived formulation is already qualified across all these criteria. Nor can a conventional corrosion-inhibitor study guarantee freedom from cracking where hydrogen sulfide and mechanical loading govern another failure mechanism. Finally, sustainability superiority is not inherent to vegetable-oil carbon: it is an outcome requiring measured formulation toxicity, biodegradation, land-use context and service-normalized lifecycle comparison.

Two falsifiable propositions emerge from this synthesis. The first is that an optimized palm-derived imidazoline, manufactured with controlled active content, can perform comparably with a benchmark inhibitor within a defined produced-water and sour-gas envelope; failure would be a clear, publishable result rather than a reason to reinterpret the chemistry as automatically green. The second proposition is that performance judged by localized damage and film persistence will often rank candidates differently from their short-term general corrosion inhibition efficiency. Multi-site-controlled studies can test this statement directly. Such a programme would move the literature beyond single-compound success stories to quantitative boundaries for realistic use.

Complementary Evidence and Boundary Cases

A useful boundary case comes from inhibitors that are not imidazolines. Wu and colleagues examined carbon-dot inhibition in hydrochloric acid and CO2-saturated saline solutions, demonstrating how a different adsorbate class may provide experimentally useful comparisons. These observations should be treated as alternative-mechanism controls rather than evidence that fatty-acid or palm-derived molecules will perform similarly. Such work reinforces the need to compare like-for-like steel, brine, temperature, dose and exposure durations before recommending a molecular family [55].

Multi-functionality may offer operational benefits, but it also complicates the interpretation of chemical efficacy. Ma and colleagues explored an imidazoline-based formulation intended to address corrosion, scale and microbial processes in CO2/H2S media, while the 2025 laurate-imidazoline work linked corrosion and scale inhibition through distinct functional groups. These results justify testing composite functionality as an explicit design hypothesis; they do not show that a palm-specific formulation is already compatible with every oilfield treatment package. Separate corrosion, scaling, microbial and interchemical-compatibility endpoints remain [56].

Guo and colleagues investigated under-deposit behaviour in a simulated CO2-saturated produced-water environment, complementing direct inhibitor-penetration studies. The combined literature indicates that a protective film measured on a clean coupon may not predict accessibility through heterogeneous corrosion products or mineral deposits. A credible test programme should compare clean and deposit-covered specimens using measured deposit thickness and composition, and explicitly quantify residual pit growth after delayed dosing.

The wider palm-sourcing literature introduces a separate evidentiary boundary. Meijaard and colleagues discuss the environmental impacts of palm oil in their broader agricultural and ecological context, whereas certification, land-conversion and bio-based chemical studies address different aspects of the supply-chain burden. Such work can justify traceability and life-cycle evaluation, but does not demonstrate that a particular corrosion-inhibitor formulation has lower ecotoxicity or better durability. Comparative environmental claims must therefore be calculated per equivalent corrosion-control service, rather than per kilogram of renewable feedstock alone [57].

Conclusions and Recommendations

Palm-derived fatty acids provide scientifically credible raw materials for designing imidazoline, amidoamine and related corrosion-inhibitor candidates. Their usefulness is conditional, however, because a renewable precursor is not identical to a characterized active molecule, a characterized molecule is not automatically a persistent protective film, and an initially protective film is not necessarily qualified for real CO2/H2S service. Molecular structure, solution partitioning, hydrolysis, pre-corrosion, deposits, wetting and flow jointly influence measured results. The evidence supports investigation and controlled comparative experimentation rather than a blanket claim of commercial readiness.

The most consequential conclusion concerns the definition of successful protection. Lower generalized corrosion rates and impressive laboratory inhibition percentages may coexist with growing local pits, restricted under-deposit delivery or a film that weakens after shutdown and redosing. Sour service additionally demands independent consideration of hydrogen-related integrity risks and suitability of the pipe material, which cannot be settled by an electrochemical efficiency number. An industry-relevant assessment therefore needs multiple representative conditions, separate localized-damage endpoints, control of steel and deposit history, and time-dependent tests before an additive can be regarded as a risk-reducing integrity measure.

The proposed six-gate Palm-Derived Corrosion Inhibitor Qualification Framework offers a transparent route from feedstock traceability through synthesis, bench chemistry, deposit testing, dynamic exposure and monitored field evidence. Every gate may return a negative result and prompt additional testing, molecular redesign or rejection. Environmental and safety qualifications run in parallel, requiring attention to traceability, biodegradability, ecotoxicity and full-formulation lifecycle burden. This design rejects greenwashing because it requires renewable and conventional alternatives to demonstrate equivalent performance first and environmental superiority second, within an explicitly defined functional comparison.

Researchers should prioritize matched molecular libraries, independent replication, complete chemical specifications and publication of negative as well as favorable tests. Petroleum operators should set risk-based acceptance criteria before testing, couple chemical trials with inspection and monitoring, and retain water management, materials selection and deposit control as potentially superior alternatives. Policymakers and procurement specialists should not award an unqualified environmental preference solely to palm-derived carbon. The appropriate aim is reliable, affordable and independently verifiable pipeline integrity, achieved with the most defensible overall technology for the operating environment [58-59].

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