

Review

Green and Bio-Based Corrosion Inhibitors for Reinforced Concrete: Recent Advances, Mechanisms, Durability, and Future Perspectives

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Abstract

Corrosion of reinforcing steel remains a major cause of premature deterioration in concrete infrastructure, motivating the development of inhibitors with lower toxicity and reduced environmental impact. This review critically examines recent advances in green and bio-based corrosion inhibitors for reinforced concrete, including plant extracts, agro-industrial residues, naturally occurring organic compounds, proteins, polysaccharides, bio-based coatings, hybrid formulations, and microbial systems. The available evidence is synthesized in terms of chemical functionality, delivery route, adsorption and film-forming mechanisms, electrochemical response, compatibility with cementitious materials, and durability under chloride- and carbonation-related exposure. Many formulations provide substantial inhibition under optimized laboratory conditions through interfacial adsorption, coordination with iron species, passive-film stabilization, suppression of anodic and cathodic reactions, and restriction of aggressive-species transport. However, reported efficiencies are not directly comparable because experimental scale, exposure conditions, dosage, steel preparation, and calculation methods vary considerably. Moreover, long-term reinforced-concrete and field studies remain scarce, while extract standardization, cement compatibility, toxicity, biodegradability, and life-cycle performance are frequently insufficiently addressed. Green and bio-based inhibitors therefore represent a promising but heterogeneous technology class. Their practical implementation requires chemically reproducible formulations, complementary electrochemical and surface evidence, concrete-scale durability assessment, environmental validation, and stage-gated progression toward monitored field applications.



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1. Introduction

Reinforced concrete (RC) underpins much of the world's built infrastructure because it combines compressive strength, formability, availability, and cost efficiency. Its long service life, however, depends strongly on the preservation of the embedded reinforcement. Cement hydration creates a highly alkaline pore solution, typically within the range required

for the spontaneous formation of a nanometric passive film on carbon steel. This protection is durable only while the chemical and transport conditions at the steel–concrete interface remain favorable. Carbonation lowers pore-solution alkalinity, whereas chlorides from marine exposure, de-icing salts, contaminated constituents, or industrial environments can destabilize passivity locally. Once corrosion starts, metal loss, loss of steel–concrete bond, and the expansive accumulation of corrosion products promote cracking, delamination, and spalling, progressively reducing structural reliability and serviceability [1–4].

Chloride-induced corrosion is especially difficult to predict because initiation is not governed by a single, universal chloride threshold. It emerges from the coupled effects of chloride binding and transport, moisture state, oxygen availability, electrical resistivity, pore-solution chemistry, steel surface condition, and heterogeneity at the steel–concrete interface [3,4]. Recent X-ray computed tomography and laser-induced breakdown spectroscopy observations have shown that interfacial macro-voids can act as local reaction environments in which gas–liquid configuration, dissolved oxygen, and chloride accumulation jointly determine where corrosion initiates. Wet–dry exposure may therefore produce initiation at lower local chloride levels than continuous immersion, illustrating why simplified tests and single-parameter service-life models can misrepresent field behavior [5].

The societal consequences are substantial: corrosion shortens maintenance cycles, increases repair and replacement demands, and consumes additional materials and energy over an asset’s life. Protection strategies include low-permeability concrete, adequate cover, supplementary cementitious materials, corrosion-resistant reinforcement, coatings, hydrophobic treatments, cathodic protection, electrochemical rehabilitation, and corrosion inhibitors [2,6,7]. No single measure is optimal for every exposure or life-cycle stage. Inhibitors are attractive because they can be admixed in new concrete, incorporated into repair systems, or, in the case of sufficiently mobile compounds, applied at the surface of existing members. Their practical value nevertheless depends on transport to the reinforcement, persistence at the interface, compatibility with cement hydration and mechanical properties, and performance under realistic exposure cycles [7–10].

Corrosion inhibitors reduce the anodic dissolution of iron, the cathodic reduction reactions, or both, commonly through modification of the passive film and/or adsorption of a barrier-forming molecular layer. Calcium nitrite remains a reference admixed inhibitor for chloride-contaminated RC, but conventional inorganic and synthetic organic formulations can raise concerns related to toxicity, handling, environmental persistence, dosage, and compatibility [8–10]. These limitations have accelerated interest in green and bio-based corrosion inhibitors. In this review, “bio-based” denotes materials wholly or partly derived from renewable biological feedstocks, whereas “green” is treated as a broader performance claim that should be supported by evidence of reduced hazard and environmental burden—not inferred merely from natural origin. This distinction is essential because extract toxicity, solvent use, energy-intensive processing, and seasonal or geographic variability can undermine an otherwise sustainable label [9,10].

Candidate bio-based inhibitors include plant extracts, agricultural and food-processing residues, amino acids, proteins, polysaccharides, microbial products, and other naturally occurring molecules. Their activity is usually associated with heteroatoms (O, N, S, and occasionally P), aromatic rings, π electrons, and polar functional groups present in polyphenols, flavonoids, tannins, alkaloids, terpenoids, lignin-derived compounds, peptides, and carbohydrates. These species may interact with steel by electrostatic attraction, donor–acceptor bonding, complex formation, hydrogen bonding, and physical or chemical adsorption. The resulting interfacial layer can occupy active sites, decrease chloride access, alter the composition and defect structure of iron oxides, and impede charge and mass transfer. Because crude extracts contain multiple compounds whose proportions depend on

feedstock and extraction conditions, an observed inhibition efficiency reflects cooperative or antagonistic interactions rather than the action of a single universal molecule [9–12].

Recent studies demonstrate the breadth of this rapidly developing field. Extracts from *Fatsia japonica* and waste *Platanus acerifolia* leaves have inhibited carbon steel in chloride-contaminated simulated concrete pore solutions, with the latter study using ultrafiltration and chromatographic analysis to enrich and identify active fractions [11,12]. Mango and Ginkgo biloba extracts have likewise combined electrochemical testing, surface characterization, density functional theory (DFT), and molecular simulation to connect adsorption behavior with molecular structure [13,14]. These advances are important because they move the literature beyond reporting a single inhibition percentage toward establishing composition–structure–adsorption–performance relationships.

Bio-derived single compounds and macromolecules offer a complementary route to better-controlled formulations. Glutamic acid achieved substantial inhibition of bare reinforcement in chloride-contaminated pore solution and showed a pronounced synergistic effect with damaged galvanized coating, supported by electrochemical, XPS, and molecular-dynamics evidence [15]. More recent work on *Cassia fistula* leaf extract reported optimum efficiencies of 85.21% by mass-loss measurements and 92.4% by potentiodynamic polarization at 5% *v/v* in simulated pore solution, together with smoother steel surfaces observed by SEM and AFM [16]. Protein- and biomass-derived systems are also expanding the design space, particularly for carbonation-affected pore solutions, where the lower pH changes both inhibitor ionization and adsorption behavior [17].

Evidence obtained in concrete remains much scarcer than evidence from simplified solutions. A recent neem-extract study evaluated reinforced cement concrete specimens exposed to sodium chloride and coupled electrochemical response with compressive strength, microscopy, GC–MS, DFT, and statistical analysis, representing a useful step toward multi-scale validation [18]. Nevertheless, high efficiencies measured during short exposures in simulated pore solutions cannot be transferred directly to structural concrete. The cement matrix can adsorb, immobilize, transform, or dilute organic species; inhibitor additions can affect setting, air content, hydration, porosity, strength, and chloride transport; and extraction solvent residues may introduce additional uncertainty. Long-term wet–dry cycling, carbonation–chloride interaction, temperature, cracking, leaching, and microbiological stability are still insufficiently characterized [9,10,18].

The broader evidence base further illustrates the progressive diversification of bio-based protection. Maize gluten meal, a co-product of wet-milling, produced inhibition efficiencies between 62.71% and 88.10% in chloride-containing simulated pore solution, with adsorption supported by SEM–EDS and ATR–FTIR [19]. In carbonated environments, asparagine and glutamine exceeded 90% efficiency at selected concentrations and were additionally evaluated for migration through ordinary Portland cement and blended-cement concretes [20]. Bio-derived coatings constitute another application route: soy-protein formulations have been examined both as stand-alone or corn-polyol-modified coatings and as abrasive-reinforced systems intended to balance corrosion resistance with steel–concrete bond [21,22]. Hybrid delivery concepts are also emerging; alanine-intercalated layered double hydroxides can simultaneously capture chloride and release an adsorbing amino-acid anion, thereby combining ion exchange with interfacial inhibition [23]. Collectively, these studies broaden the field beyond crude botanical extracts and point toward engineered bio-based formulations, carriers, and synergistic systems.

A further limitation is the lack of harmonization. Studies differ in steel grade and surface preparation, pore-solution composition, chloride concentration, pH, exposure time, inhibitor dosage basis, extraction protocol, and electrochemical calculation method. The term “inhibition efficiency” may derive from corrosion current density, polarization

resistance, impedance parameters, or mass loss, which are not always directly comparable. Botanical name alone is also inadequate for reproducibility: plant part, maturity, provenance, drying, particle size, solvent-to-solid ratio, extraction temperature and time, purification, storage, and chemical fingerprint should be reported. Recent broader reviews of plant-derived inhibitors similarly identify concentration, temperature, compositional variability, extraction, and scale-up as persistent obstacles [24–26]. Mechanistic interpretation is strongest when electrochemical data are corroborated by surface chemistry and morphology, while computational results should support—not replace—experimental adsorption evidence [9,10,12–16,24–26].

Previous reviews have established classifications, mechanisms, and early evidence for conventional and green inhibitors in RC [9,10]. At the same time, critical syntheses of corrosion in carbonated concrete emphasize that moisture state, pore structure, ionic composition, and exposure history govern whether depassivation develops into damaging propagation [27,28]. Since the publication of the principal inhibitor reviews, the field has advanced toward fractionated waste-derived extracts, amino-acid/coating synergies, protein-based inhibitors, direct testing in concrete, and coupled electrochemical–spectroscopic–computational workflows [12,15–23]. A critical update is therefore needed that distinguishes chemical promise from construction-ready performance and evaluates sustainability claims with the same rigor applied to corrosion measurements.

Previous reviews have provided valuable classifications of green and conventional corrosion inhibitors according to their biological or chemical origin, active constituents, adsorption behavior, electrochemical mechanism, and maximum reported inhibition efficiency [9,10,24–26,29–32]. These contributions have established the chemical and mechanistic basis of the field. However, most previous syntheses primarily organize the available formulations or summarize their performance under particular experimental conditions. Comparatively less attention has been given to determining whether the evidence supporting a given inhibitor is sufficiently mature for progression from controlled electrolyte testing to mortar, reinforced concrete, long-term exposure, and field implementation.

The principal contribution of the present review is therefore not an additional source-based classification or a ranking of maximum inhibition efficiencies. Instead, it integrates inhibitor chemistry, electrochemical evidence, delivery route, cementitious-material compatibility, transport to the reinforcement, durability, reproducibility, environmental performance, and scale-up within a unified evaluation framework. This approach distinguishes chemical inhibition potential demonstrated in simulated pore solutions from construction-relevant performance and long-term protection. It also addresses the methodological problem created when high efficiencies obtained using different electrochemical or gravimetric methods and exposure periods are interpreted as equivalent indicators of practical readiness.

The four-level evidence hierarchy and the phased transition and decision framework presented in this review were developed by the authors as an original synthesis of the limitations and validation requirements repeatedly identified across the reviewed literature. They were not reproduced or directly adapted from a previously published inhibitor-classification or technology-readiness system. Nevertheless, their scientific basis is informed by established corrosion mechanisms, standardized electrochemical and concrete-testing procedures, and previous critical assessments of inhibitor performance and reinforced-concrete durability [4,5,9,10,18,20–29,33–42]. The framework converts this dispersed evidence into sequential and measurable decision stages, allowing researchers and practitioners to identify the current maturity of an inhibitor system, determine the evidence still required, and avoid extrapolating short-term solution performance directly to durable field protection.

Table 1 compares the scope of representative previous reviews with that of the present study and identifies the specific gap addressed by the proposed framework.

Table 1. Comparison between previous reviews and the scope and original contribution of the present study.

Review	Principal Scope and Classification Approach	Treatment of Reinforced-Concrete Application	Treatment of Sustainability	Evidence Maturity and Laboratory-to-Field Transition
Zomorodian and Behnood [9]	Conventional and green inhibitors classified according to type, origin, and corrosion-inhibition behavior	Discusses inhibitor use and performance in reinforced concrete	Introduces environmental advantages and limitations of green alternatives	Does not establish a staged evidence hierarchy for progression from solution testing to field validation
Casanova et al. [10]	Green inhibitors for chloride-induced corrosion, emphasizing sources, mechanisms, and reported performance	Focuses directly on reinforced-concrete corrosion and concrete-relevant applications	Discusses environmental motivation and challenges associated with green inhibitors	Identifies research limitations but does not provide measurable progression or decision criteria
Holla et al. [24]	Plant extracts for different steel systems, organized mainly by botanical source and inhibition performance	Reinforced concrete is included within a broader steel-corrosion context	Natural origin and environmental advantages are discussed	Does not distinguish systematically among pore-solution, mortar, concrete, and field evidence
Sheydaei [25]	Plant-derived inhibitors classified by extract source, composition, and inhibition response	Broad metallic-corrosion scope; concrete is not the exclusive application	Reviews advantages and limitations of plant-derived products	Does not evaluate construction readiness or provide a stage-gated validation pathway
Zakeri et al. [26]	Concise synthesis of plant extracts for ferrous metals, emphasizing adsorption and efficiency	Limited reinforced-concrete-specific evaluation	Sustainability is considered primarily in relation to renewable origin and lower toxicity	No evidence-level or laboratory-to-field decision framework
Wang et al. [29]	Organic inhibitors under chloride attack, including mechanisms and evaluation methods	Strong focus on reinforced concrete and corrosion-testing methods	Environmental performance is not the principal organizing criterion	Discusses evaluation methods but does not integrate them into a four-level maturity framework
Barbu et al. [30]	Critical interdisciplinary evaluation of plant extracts and their eco-friendly claims	Broader corrosion-inhibition perspective rather than exclusive reinforced-concrete application	Strong attention to extraction, toxicity, reproducibility, and sustainability claims	Does not provide a reinforced-concrete-specific transition framework
Ayaz et al. [31]	Polymer and eco-friendly inhibitors for reinforced concrete	Reviews mechanisms, materials, and corrosion-protection applications	Considers eco-friendly formulations and future development	Does not establish quantitative evidence levels or decision gates for field progression
Wang et al. [32]	Biomass-derived inhibitors for metallic-corrosion control	Broad metal-corrosion coverage; reinforced concrete is one potential context	Emphasizes biomass utilization and environmental relevance	Does not distinguish systematically between chemical screening and construction-scale validation
Present review	Integrates source, active chemistry, inhibition mechanism, delivery route, electrochemical response, cement compatibility, durability, and environmental evidence	Distinguishes simulated pore solution, mortar, reinforced concrete, coatings, transport, long-term exposure, and field relevance	Separates biological origin from demonstrated environmental performance and identifies minimum validation needs	Introduces an original four-level evidence hierarchy and phased decision framework for translating inhibitor systems from laboratory screening to field-relevant application

Accordingly, this review critically synthesizes recent progress in green and bio-based inhibitors for reinforced concrete, with emphasis on (i) biological source and extraction or purification route; (ii) anodic, cathodic, mixed, and film-forming mechanisms; (iii) evidence

from simulated pore solutions, mortar, and concrete; (iv) effects on fresh, mechanical, transport, and durability properties; (v) electrochemical, surface-analytical, and computational methods used to substantiate performance; and (vi) reproducibility, toxicity, scalability, life-cycle implications, and standardization. By separating results obtained in acidic media from those generated under concrete-relevant alkaline conditions, and by comparing short-term efficiency with durability-relevant evidence, the review aims to define the research pathway required to translate promising bio-derived chemistries into reliable, verifiably sustainable protection systems for RC infrastructure.

The remainder of this review is organized as follows. Section 2 describes the literature-search and evidence-synthesis methodology. Section 3 classifies the inhibitor systems and examines their active components and electrochemical protection mechanisms. Section 4 evaluates experimental evidence, analytical methods, cementitious compatibility, transport, and long-term durability. Section 5 integrates the principal findings in terms of reproducibility, environmental performance, technology readiness, and field translation, followed by the main conclusions in Section 6.

2. Review Methodology

2.1. Information Sources and Search Strategy

This study was conducted as a structured critical review of green and bio-based corrosion inhibitors relevant to reinforcing steel and cement-based materials. The literature search was performed using Scopus, Web of Science, ScienceDirect, and Google Scholar. Scopus and Web of Science were used as the principal multidisciplinary citation databases; ScienceDirect was used to identify relevant full-text publications in corrosion, materials science, and cement-based materials; and Google Scholar was used as a complementary source for citation tracing and the identification of additional relevant publications.

The search covered the literature available from database inception to 31 July 2026. Only publications written in English were considered. Search expressions combined terms related to the structural material, corrosion process, inhibitor origin, and exposure environment. Representative Boolean combinations included the following: (“reinforced concrete” OR “reinforcing steel” OR rebar OR “carbon steel”) AND (corrosion OR chloride OR carbonation) AND (“green corrosion inhibitor” OR “bio-based corrosion inhibitor” OR “plant extract” OR “biomass-derived inhibitor” OR “amino acid” OR protein OR polysaccharide OR microbial) AND (“simulated concrete pore solution” OR mortar OR concrete). Complementary searches included combinations of these terms with adsorption, passive film, electrochemical impedance spectroscopy, polarization resistance, mass loss, migrating inhibitor, reinforcement coating, transport, cement compatibility, toxicity, biodegradability, and life-cycle assessment.

The search was iterative rather than restricted to a single query. Reference lists from relevant primary studies and previous reviews were examined to identify additional publications, foundational corrosion literature, testing standards, and technical recommendations. The search was updated before resubmission to verify the inclusion of the most recent studies published in 2025 and 2026.

2.2. Eligibility and Selection Criteria

Peer-reviewed research articles constituted the principal evidence base. Review articles were included to establish the state of knowledge, identify previous classification approaches, and support the critical comparison of research gaps. Standards and institutional technical recommendations were included when they provided accepted procedures or criteria for corrosion assessment, electrochemical measurements, concrete durability, biodegradability, environmental evaluation, or life-cycle assessment. Foundational books

and technical monographs were retained only when required to establish generally accepted principles of reinforced-concrete corrosion and inhibitor application.

Publications were eligible when they addressed bio-based, naturally derived, biomass-derived, or potentially low-toxicity corrosion inhibitors and provided information relevant to reinforcing steel, simulated concrete pore solutions, cement paste, mortar, reinforced concrete, reinforcement coatings, or inhibitor transport through cementitious materials. Studies reporting quantitative corrosion parameters, including corrosion current density, polarization resistance, charge-transfer resistance, corrosion rate, mass loss, or inhibition efficiency, were prioritized for performance assessment. Studies providing chemical, surface, computational, mechanical, transport, environmental, or durability evidence were also included when they contributed to the interpretation of inhibition mechanisms or practical applicability.

Publications were excluded from the principal evidence synthesis when they were unrelated to steel corrosion, addressed metallic systems without a transferable connection to reinforcing steel, lacked relevance to alkaline or cement-based environments, did not provide sufficient information to identify the inhibitor or exposure conditions, duplicated evidence already reported in a more complete publication, or were unavailable as full-text English-language documents. Studies conducted exclusively in strongly acidic media were not used as direct evidence of performance in reinforced concrete; they were considered only when they provided relevant information on extraction, chemical composition, adsorption, or molecular structure–activity relationships. Studies with incomplete quantitative information were excluded from direct numerical comparison but could be retained for qualitative or mechanistic discussion.

2.3. Evidence Base and Synthesis Approach

The final evidence base comprised 84 sources: 67 peer-reviewed journal publications, including 55 primary research articles and 12 review articles; 14 standards or institutional technical documents; and 3 foundational books or technical monographs. Of the 84 sources, 52 were published from 2020 onward, 15 were published from 2024 onward, and 8 were published in 2025–2026. The latter group included recent studies on *Cassia fistula* leaf extract, glutenin, neem extract in reinforced concrete, ovalbumin, and other contemporary inhibitor systems or critical reviews. This distribution confirms that the synthesis emphasizes recent developments while retaining foundational references required for electrochemical interpretation and standardized testing.

For each eligible publication, information was extracted concerning inhibitor origin and preparation, active constituents or functional groups, application route, experimental medium, steel condition, chloride concentration, pH, inhibitor dosage, exposure time, electrochemical or gravimetric method, reported inhibition efficiency, surface characterization, cement compatibility, and experimental scale. The evidence was synthesized critically rather than statistically because of substantial heterogeneity in materials, exposure conditions, dosage definitions, experimental duration, and calculation methods. Consequently, inhibition efficiencies obtained using different techniques were not considered directly interchangeable or used to establish an absolute ranking among inhibitor systems.

3. Green and Bio-Based Corrosion Inhibitors for Reinforced Concrete

3.1. Conceptual Basis and Classification

Green and bio-based inhibitors comprise a chemically diverse group rather than a single class of protective agents. In reinforced concrete, they may be classified according to origin (plant, agricultural residue, amino acid, protein, polysaccharide, microbial product, or other renewable feedstock), application route (admixture, migrating treatment, surface-

applied formulation, reinforcement coating, or carrier-loaded system), and electrochemical action (anodic, cathodic, or mixed-type inhibition) [9,10,24–26]. These classifications are complementary. A plant extract, for example, describes origin but not whether its active constituents suppress iron dissolution, modify oxygen reduction, or form a mixed protective film. Likewise, the term “migrating inhibitor” identifies a delivery function and does not establish either biological origin or environmental safety [8–10]. A source-based classification alone does not fully describe inhibition behavior, particularly for plant extracts and biomass-derived formulations containing multiple constituents in variable proportions. Similar functional groups may occur in chemically different feedstocks, while extracts from the same biological source may exhibit different performance because of variations in plant part, maturity, extraction solvent, temperature, fractionation, and storage. Consequently, the source categories used in Section 3 are intended to describe feedstock provenance, production route, reproducibility challenges, and sustainability-related considerations rather than to imply a unique inhibition mechanism or intrinsic performance level.

The present review therefore uses a complementary two-axis classification. The first axis organizes inhibitor systems by source and formulation route, including plant-derived extracts, agro-industrial or biomass residues, chemically defined natural compounds, bio-based coatings, and hybrid systems. The second axis, developed in Section 4.5 and organizes the same evidence according to dominant active motifs and protection mechanisms, including polyphenol-rich and aromatic systems, polysaccharides and natural gums, amino acids and proteins, organic acids and chelating molecules, barrier-forming coatings, controlled-release systems, and microbial or biofilm-mediated processes. This dual classification preserves information on material origin while allowing chemically different sources with comparable functional groups or inhibition mechanisms to be evaluated together.

The distinction between green and bio-based is particularly important. A bio-based material is derived wholly or partly from renewable biological resources; however, its origin alone does not demonstrate low toxicity, biodegradability, reduced life-cycle impact, or safe extraction. Conversely, an inhibitor produced synthetically may have a favorable hazard profile without being bio-based. Recent reviews frequently use “green,” “eco-friendly,” “natural,” and “sustainable” interchangeably, although these terms refer to different attributes and are rarely supported by standardized ecotoxicity or life-cycle data [9,10,24–26]. For this reason, the present review treats biological origin as a verifiable material characteristic, whereas environmental performance is considered a claim requiring independent evidence.

Within reinforced concrete, the most relevant systems are those capable of operating in alkaline pore solutions and remaining effective after chloride ingress or carbonation. Results obtained in hydrochloric or sulfuric acid can reveal adsorption tendencies and structure–activity relationships, but they cannot be transferred directly to cementitious environments. Protonation state, steel surface oxides, competing ions, calcium complexation, and inhibitor solubility differ substantially between acidic electrolytes and the pH range of sound or carbonated concrete [3,4,9,10,27,28]. Accordingly, the evidence discussed below prioritizes simulated concrete pore solutions, mortar, and concrete, while acid-medium studies are used only to support chemical interpretation.

3.2. Plant-Derived Corrosion Inhibitors

Plant extracts are the most extensively investigated bio-based family because leaves, bark, roots, seeds, fruits, peels, and processing residues contain mixtures of polyphenols, flavonoids, tannins, alkaloids, terpenoids, saponins, proteins, sugars, and organic acids [9,10,24–26]. Their inhibitory activity is commonly associated with aromatic rings, π -electron systems, and functional groups containing O, N, or S. Hydroxyl, carbonyl, car-

boxyl, ether, amine, amide, and heterocyclic groups can interact with metallic iron, iron oxides, calcium-rich phases, or dissolved species. Nevertheless, botanical origin does not guarantee reproducible composition. Genotype, plant age, harvest season, geographic origin, drying, grinding, solvent polarity, liquid-to-solid ratio, temperature, extraction time, purification, and storage can all change the concentration and relative proportion of active molecules [10,12,24–26].

Recent concrete-relevant studies illustrate this diversity. *Fatsia japonica*, mango, *Ginkgo biloba*, *Cassia fistula*, neem, ginger, licorice, pomegranate, *Psoralea corylifolia*, olive, and eucalyptus extracts have been evaluated using reinforcing or carbon steel under alkaline, chloride-contaminated, carbonated, mortar, or concrete conditions [11,13,14,16,18,43–48]. Ginger extract reduced chloride-induced corrosion in simulated pore solution, whereas licorice extract combined electrochemical response, XPS, FTIR, SEM, and DFT to link protection with adsorption of its organic constituents [43,44]. Pomegranate-peel extract was extended beyond solution testing to mortar, providing stronger construction relevance than studies confined to polished steel in electrolytes [45]. Neem, olive, and eucalyptus studies likewise illustrate the gradual transition toward reinforced-concrete specimens and mechanical or durability-related measurements [18,47,48].

This body of evidence confirms that plant-derived inhibitors are chemically promising but also exposes a central reproducibility problem. Botanical species alone does not define an inhibitor: plant part, maturity, provenance, drying, solvent polarity, liquid-to-solid ratio, temperature, extraction time, fractionation, storage, and chemical fingerprint determine which molecules reach the steel surface [10–14,24–26,43–48]. Ultrasound-assisted enzymatic extraction and ultrafiltration of waste *Platanus acerifolia* leaves, for example, enriched active fractions and improved protection relative to the untreated extract [12]. Plant-derived systems should therefore be reported as process-defined formulations rather than only by common or botanical name.

3.3. Agro-Industrial and Biomass-Waste-Derived Inhibitors

Agricultural and food-processing residues are particularly aligned with the circular-economy dimension of the review. Maize gluten meal, waste *Platanus* leaves, pomegranate peel, and coconut coir dust convert low-value biomass streams into corrosion-control candidates [12,19,45,49]. Maize gluten meal extract, a wet-milling co-product, produced reported efficiencies of 62.71–88.10% in simulated pore solution containing 3 wt.% NaCl; electrochemical measurements, SEM-EDS, ATR-FTIR, and surface analysis associated protection with adsorption of peptide- and amide-containing constituents [19]. Coconut coir dust extract has been studied in chloride-contaminated concrete pore solution, while pomegranate-peel extract has been evaluated in simulated pore solution and mortar [45,49].

Waste origin strengthens resource-efficiency arguments but does not by itself prove sustainability. Residue composition may vary with cultivar, processing history, moisture, ageing, and contamination; extraction may consume solvents and energy; and low or variable yield can limit scalability [12,19,24–26,45,49]. The strongest studies in this category combine waste-stream identification with extraction yield, chromatographic or spectroscopic fingerprinting, inhibitor dosage, and concrete-relevant performance. Without these data, circularity claims remain qualitative.

3.4. Naturally Occurring Organic Compounds

Naturally occurring organic compounds provide a more chemically defined alternative to multicomponent extracts. Glutamic acid, asparagine, glutamine, serine, cysteine, alanine, and related amino acids contain carboxylate, amino, amide, hydroxyl, or sulfur-bearing groups capable of adsorption and Fe–organic coordination [15,20,23,50]. Glutamic acid

inhibited bare steel in chloride-contaminated pore solution and produced marked synergy with scratched galvanized reinforcement [15]. Asparagine and glutamine exceeded 90% efficiency at selected concentrations in carbonated pore solution and were additionally assessed for migration through ordinary Portland cement and blended-cement concrete [20]. Serine and cysteine also achieved efficiencies above 90% in an alkaline solution simulating carbonated concrete, where electrochemical and surface evidence indicated predominantly anodic inhibition and Fe(III)-complex formation [50].

Compared with crude extracts, these compounds offer defined molecular mass, purity, concentration, and functional chemistry, thereby facilitating reproducibility and computational interpretation [15,20,23,50]. Their limitations are different: high water solubility may promote leaching, strong interaction with cement hydrates may reduce the fraction reaching the reinforcement, and concentration-dependent effects on hydration or pore structure require evaluation. Performance must therefore be established not only on immersed steel but also through transport, retention, and compatibility tests in mortar and concrete [9,10,20,23].

3.5. Bio-Based Coatings and Protective Films

Bio-based coatings use renewable polymers or molecules as a continuous protective layer rather than relying solely on inhibitor transport through concrete. Soy-protein isolate and soy-protein/corn-derived polyol formulations have been investigated for reinforcing steel, including repair of damaged epoxy-coated bars [21,22]. These coatings combine polar-group interaction with steel and a physical barrier to water, oxygen, and chloride. Reported work has considered abrasion resistance, electrochemical behavior, and steel–concrete bond, which are essential because a highly resistive coating is not useful if it delaminates, is damaged during placement, or compromises load transfer [21,22]. Reviews of bio-based treatments further identify renewable coatings as a promising but comparatively underdeveloped protection route for cementitious infrastructure [10,21,22].

The principal challenges are moisture sensitivity, curing, adhesion to mill-scaled or rusted reinforcement, thickness control, abrasion during handling, bond with concrete, and repairability. Long-term performance under cracking, wet–dry cycling, alkaline ageing, and sustained chloride exposure remains insufficiently documented [21,22]. Thus, bio-based coatings should be evaluated as reinforcement–coating–concrete systems rather than only as coated metal coupons.

3.6. Hybrid Bio-Based Inhibitor Systems

Hybrid systems couple a bio-derived active molecule with an inorganic carrier, metallic coating, or complementary inhibitor to address several deterioration processes simultaneously. Alanine-intercalated layered double hydroxides capture chloride while releasing alanine anions that adsorb on steel and modify the passive film [23]. Glutamic acid combined with zinc from damaged galvanized reinforcement provides another form of synergy, increasing protection of scratched areas beyond that obtained from the individual components [15]. These systems move the field from freely dissolved extracts toward controlled delivery, ion exchange, and complementary barrier/passivation mechanisms.

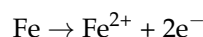
Hybridization can improve persistence and reduce the inhibitor concentration needed in the pore solution, but it also increases formulation complexity. Carrier synthesis, loading capacity, release kinetics, competition with hydroxide and carbonate ions, dispersion in cement, effects on hydration, and cost must be evaluated [15,23]. A hybrid system should only be described as bio-based when the origin and contribution of its renewable fraction are explicitly reported; an inorganic host does not become bio-based merely because it carries an amino acid.

3.7. Shared Inhibition Mechanisms in Cementitious Environments

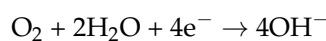
3.7.1. Electrochemical Basis of Reinforcing-Steel Corrosion

Corrosion of reinforcing steel is an electrochemical process involving spatially coupled anodic and cathodic reactions at the steel–concrete interface. In sound concrete, the highly alkaline pore solution promotes the formation of a thin passive oxide film that limits the anodic dissolution of iron. Carbonation reduces pore-solution alkalinity, whereas chloride ions can destabilize the passive film locally and promote active corrosion, particularly at heterogeneous steel–concrete interfacial regions [3,4,8–10].

At anodic sites, metallic iron is oxidized according to the following:



The released electrons move through the steel toward cathodic regions. Under the aerated alkaline conditions typical of concrete, the principal cathodic reaction is oxygen reduction:



Ionic transport through the concrete pore solution completes the electrochemical circuit. The ferrous ions generated at anodic sites subsequently react with hydroxide and oxygen to form iron hydroxides and oxides. Their accumulation can produce expansive stresses, cracking, delamination, and eventual loss of reinforcement cross-section and steel–concrete bond [2–4].

Corrosion inhibitors act by interfering with one or more stages of this coupled process. Anodic inhibitors reduce iron dissolution or promote the formation and stabilization of a passive film. Cathodic inhibitors decrease oxygen-reduction kinetics or reduce the number of electrochemically active cathodic sites. Mixed-type inhibitors affect both partial reactions, commonly through adsorption of organic molecules or formation of a protective interfacial film. Coatings and high-molecular-weight bio-based systems may act predominantly through barrier and transport effects, restricting the access of chloride, water, and oxygen rather than selectively blocking a single charge-transfer reaction. Hybrid systems may additionally capture chloride, release an active molecule, or combine passive-film stabilization with interfacial adsorption [8–17,20–23].

Accordingly, the mechanisms summarized in Table 2 are linked to the electrochemical step predominantly affected: suppression of anodic iron dissolution, retardation of the cathodic oxygen-reduction reaction, stabilization or restoration of passivity, mixed inhibition of both partial reactions, or limitation of reactant transport. Because plant extracts and biomass-derived formulations contain multiple active constituents, their observed protection frequently results from simultaneous or synergistic mechanisms rather than from complete blockage of a single electrochemical step.

3.7.2. Adsorption and Barrier-Film Formation

Adsorption is the mechanism most frequently proposed for organic and plant-derived inhibitors. Molecules may initially approach a charged steel or oxide surface through electrostatic attraction and subsequently form stronger donor–acceptor interactions involving heteroatom lone pairs, π electrons, and vacant iron d orbitals [9,10,13–17]. Physical adsorption is generally favored by electrostatic interactions and is sensitive to temperature and ionic strength, whereas chemisorption involves coordinate bonding or surface complex formation. In multicomponent extracts, both processes may occur simultaneously, and fitting a Langmuir isotherm alone is insufficient to prove a particular adsorption mechanism [10,13–17].

The protective layer reduces the fraction of electrochemically active surface, limits chloride access, and impedes charge transfer. EIS commonly identifies this behavior through increased polarization or charge-transfer resistance and decreased double-layer capacitance, while polarization curves show lower corrosion current density [11–18]. Surface confirmation is essential: FTIR or Raman spectroscopy can identify organic functional groups; XPS can detect Fe–O, Fe–N, or metal–organic interactions and changes in iron oxidation state; SEM and AFM reveal reduced damage and surface roughness; and GC–MS or HPLC can connect electrochemical behavior to particular extract constituents [11–18]. The strongest mechanistic studies therefore triangulate electrochemical, chemical, and morphological evidence rather than inferring film formation from inhibition efficiency alone.

3.7.3. Passive-Film Stabilization and Complex Formation

Some bio-based molecules do more than create an external barrier: they interact with the native iron-oxide film or participate in the formation of new protective complexes. Carboxylate and amino groups in amino acids can coordinate with iron species and alter the $\text{Fe}^{2+}/\text{Fe}^{3+}$ balance, while polyphenols and tannin-like molecules may form poorly soluble iron–organic complexes [15,17,20,23]. Glutamic acid adsorption was linked to donor–acceptor interactions involving nitrogen and iron, and XPS supported the formation of a chemically bonded protective layer [15]. For glutenin, carboxylate and amino functionalities from constituent amino acids were associated with adsorption on corrosion products and formation of a dense film in carbonated pore solution [17]. In LDHs-ALA, protection involves two coupled processes: competitive chloride uptake by the layered host and adsorption of released alanine on the steel surface [23].

The cementitious environment complicates these interactions. Calcium and alkali ions can form complexes with inhibitor molecules, cement hydrates can adsorb organic species before they reach the reinforcement, and carbonation changes both surface charge and molecular ionization [9,10,17,20,23,27,28]. Consequently, an inhibitor that adsorbs strongly on polished steel in a simplified electrolyte may become immobilized within cement paste or may interfere with hydration. Mechanistic claims must therefore be verified progressively in pore solution, cement paste or mortar, and finally reinforced concrete.

3.7.4. Anodic, Cathodic, and Mixed Electrochemical Effects

Anodic inhibitors primarily suppress iron dissolution or support passivity, whereas cathodic inhibitors retard oxygen reduction or other cathodic processes. Most plant extracts and amino-acid-based compounds are reported as mixed-type inhibitors because they reduce both anodic and cathodic current without producing a sufficiently large displacement of corrosion potential to justify a purely anodic or cathodic classification [9–17,20]. This classification should be based on polarization behavior and supported by mechanistic evidence; a single shift in open-circuit potential is not conclusive. Concentration is also critical. Incomplete surface coverage can leave a small anodic area coupled to a large cathodic surface, potentially intensifying localized attack, while excessive organic dosage may affect hydration, entrain air, or increase transport pathways [8–10].

Synergistic systems can address more than one controlling process. Glutamic acid combined with zinc from a damaged galvanized coating reached substantially greater protection than either the unprotected scratched coating or the inhibitor-free condition [15]. LDHs-ALA couples chloride binding with inhibitor release [23], and soy-protein coatings combine chemical interaction with a physical barrier [21,22]. These approaches suggest that future bio-based systems may be more reliable when designed as multifunctional formulations rather than as unprocessed extracts.

3.8. Comparative Synthesis of the Available Evidence

Table 2 groups the available evidence by inhibitor family rather than listing isolated studies. The table also identifies the electrochemical step predominantly affected by each inhibitor family, distinguishing anodic suppression, cathodic retardation, mixed inhibition, passive-film stabilization, and transport-controlled protection. Because these source-based families may contain overlapping active compounds and functional groups, Table 2 should be interpreted together with the structure–function classification provided in Table 4. This organization permits comparison of biological sources, dominant functional chemistry, proposed protection mechanisms, maturity of experimental evidence, and unresolved limitations. The reported efficiencies should not be interpreted as a direct ranking because electrolyte composition, chloride content, steel preparation, dosage, exposure duration, and calculation method differ among studies. Particular attention is therefore given to whether each family has been examined only in solution or extended to mortar, concrete, coating, or migration assessment [11–26].

Table 2. Comparative synthesis of the principal families of bio-based and naturally derived corrosion inhibitors investigated for reinforced-concrete applications.

Inhibitor Family	Representative Sources/Systems	Predominant Active Groups, Protection Mechanism, and Electrochemical Step Affected	Evidence Level and Principal Limitations	Representative References
Plant-derived corrosion inhibitors	Fatsia japonica, mango, Ginkgo biloba, Cassia fistula, neem, ginger, licorice, pomegranate, Psoralea corylifolia, olive, and eucalyptus extracts	Polyphenols, flavonoids, tannins, alkaloids, and other oxygen- or nitrogen-containing compounds promote multicomponent adsorption, surface complexation, and barrier-film formation. Most act as mixed-type inhibitors by reducing anodic iron dissolution and cathodic oxygen reduction, while selected constituents may additionally stabilize the passive film.	Broadest experimental base, including pore solution, mortar, and a smaller number of reinforced-concrete studies. Major limitations are compositional variability, incomplete chemical fingerprinting, and short exposure periods.	[11,13,14,16,18,24–26,43–48]
Agro-industrial and biomass-waste-derived inhibitors	Waste Platanus leaves, maize gluten meal, pomegranate peel, and coconut coir dust	Polyphenolic fractions, peptides, amide groups, and lignocellulosic extractives adsorb through O- and N-containing sites and form protective interfacial layers. Their action is predominantly mixed, suppressing anodic dissolution and cathodic oxygen reduction while restricting chloride and reactant transport.	Strong circular-economy relevance; evidence extends from pore solutions to mortar or concrete for selected residues. Extraction yield, batch variability, ageing, and scale-up remain insufficiently quantified.	[12,19,24–26,45,49]
Naturally occurring organic compounds	Glutamic acid, asparagine, glutamine, serine, cysteine, and alanine	Carboxylate, amino, amide, hydroxyl, and sulfur-containing groups promote Fe–organic coordination, adsorption, complex formation, and passive-film stabilization. Depending on molecular structure and concentration, these compounds act predominantly on anodic iron dissolution or as mixed-type inhibitors affecting both partial reactions.	Chemically defined and reproducible. Some studies report >90% efficiency and assess migration or synergy, but retention, leaching, dosage, and cement compatibility require concrete-scale validation.	[15,20,23,50]

Table 2. *Cont.*

Inhibitor Family	Representative Sources/Systems	Predominant Active Groups, Protection Mechanism, and Electrochemical Step Affected	Evidence Level and Principal Limitations	Representative References
Bio-based coatings and protective films	Soy-protein isolate and soy-protein/corn-derived polyol coatings, including abrasive-modified formulations	Continuous polymeric barriers and polar-group interactions reduce electrolyte access to steel. Their principal action is transport and interfacial limitation rather than selective blockage of one reaction; restriction of chloride, water, and oxygen indirectly suppresses both anodic dissolution and cathodic oxygen reduction.	Evaluated through electrochemical, abrasion, and bond-related tests. Field relevance depends on coating continuity, damage tolerance, alkaline ageing, and preservation of steel-concrete bond.	[10,21,22]
Hybrid bio-based inhibitor systems	Alanine-intercalated LDH and glutamic-acid/galvanized-steel combinations	Coupled chloride capture, controlled release, amino-acid adsorption, passive-film modification, and complementary metallic protection affect multiple stages. Chloride removal delays depassivation, released molecules suppress anodic and cathodic reactions, and protective films limit interfacial charge and mass transfer.	Multifunctional protection is promising, but renewable content, carrier synthesis, release kinetics, cost, and effects on cement hydration must be transparently reported.	[15,23]

3.9. Current Limitations and Requirements for Practical Translation

Despite encouraging laboratory results, most bio-based inhibitors remain at an early technology-readiness level. The dominant evidence comes from short-term immersion in simulated pore solutions, frequently using polished steel surfaces and inhibitor concentrations that may not be attainable at reinforcement depth [9,10,24–26]. Only a smaller group of studies has examined migration through concrete, effects on bond, compatibility with cement hydration, mechanical behavior, or corrosion response in reinforced concrete [18,20–22]. Even fewer studies address cracked concrete, combined carbonation and chloride exposure, sustained wet–dry cycling, temperature variation, leaching, ageing of the organic film, or microbial degradation.

Reproducibility requires chemical standardization. At minimum, studies should report taxonomic identification, plant part or residue stream, origin, pretreatment, solvent, extraction yield, process conditions, storage, major chemical constituents, and a quantitative fingerprint [10,12,24–26]. Corrosion testing should report steel composition and preparation, solution chemistry, pH evolution, chloride-to-hydroxide ratio, inhibitor concentration on a clearly defined basis, exposed area, replicate number, immersion time, equivalent-circuit selection, and uncertainty. Inhibition efficiency should always be accompanied by the underlying corrosion current, resistance, or mass-loss values and by the measurement time [9,10].

Finally, sustainability must be demonstrated beyond renewable origin. Solvent recovery, water and energy demand, seasonal feedstock supply, extraction yield, shelf life, toxicity, biodegradation products, competition with food uses, and life-cycle impacts should be compared with conventional inhibitors [9,10,24–26]. A credible route toward application therefore requires a staged validation framework: molecular and electrochemical screening; compatibility with cement hydration and fresh properties; transport and retention in mortar or concrete; long-term corrosion testing under cyclic exposure; mechanical and bond assessment; toxicological and environmental evaluation; and pilot-scale validation. Until these stages are addressed, high short-term efficiency in simulated pore solution should be regarded as evidence of chemical potential rather than proof of durable field performance.

4. Performance Assessment and Durability of Green and Bio-Based Corrosion Inhibitors

Green and bio-based corrosion inhibitors cannot be evaluated solely through a maximum inhibition-efficiency value. Their performance depends on the experimental scale, steel condition, alkalinity, chloride-to-hydroxide ratio, carbonation state, inhibitor concentration, exposure time, oxygen and moisture availability, and the method used to calculate efficiency [3–5,9,10,27,28]. A rigorous assessment must therefore distinguish chemical activity in a simplified electrolyte from persistence and compatibility in cementitious systems. This section examines the principal levels of evidence and the analytical methods used to substantiate electrochemical, interfacial, and durability claims.

4.1. Levels of Experimental Evidence

Evidence for a new inhibitor normally begins with molecular or extract characterization and electrochemical screening. Simulated concrete pore solutions are useful because pH, chloride content, inhibitor dosage, and exposure time can be controlled, and the steel surface can be examined without the transport restrictions imposed by cement paste [10–17,19,20,23,43–50]. These tests are indispensable for identifying concentration ranges, anodic or cathodic tendencies, adsorption behavior, and early film formation. Nevertheless, they normally use polished or freshly prepared steel, a spatially uniform electrolyte, and inhibitor concentrations that are immediately available at the metal surface. These conditions differ markedly from reinforcement covered by mill scale, embedded behind several centimeters of heterogeneous concrete, or exposed through cracks and partially saturated pores [4,5,27,28].

The next level of evidence is provided by cement paste and mortar. At this scale, adsorption by hydrates, calcium complexation, tortuosity, pore refinement, and inhibitor retention begin to influence the concentration reaching the steel. Mortar studies can also reveal whether the formulation alters setting, hydration, porosity, water absorption, chloride transport, or mechanical response. Pomegranate-peel extract has been evaluated in both simulated pore solution and mortar [45], while amino-acid-based inhibitors have been examined for migration through ordinary Portland cement and blended-cement concrete [20]. Such extensions are substantially more informative than solution-only measurements, although mortar specimens still do not reproduce reinforcement congestion, realistic cover, cracks, or structural stress.

Reinforced-concrete testing provides stronger construction relevance because inhibitor transport, steel–concrete interfacial conditions, cover depth, resistivity, moisture gradients, and mechanical compatibility act simultaneously. Neem-containing reinforced concrete, soy-based reinforcement coatings, and selected migrating amino-acid systems have been assessed at this level [18,20–22]. The highest level of confidence requires cyclic chloride or carbonation exposure, wet–dry changes, cracking, leaching, ageing, and preferably field or pilot-scale validation. Figure 1 summarizes this evidence ladder. Progression from left to right should be interpreted as increasing confidence in application, not as a mandatory linear sequence for every formulation.

The evidence hierarchy proposed here is an original analytical framework developed by the authors from the recurring methodological and translational gaps identified during the critical synthesis. It is not intended as a universal certification or formal technology-readiness scale, nor was it directly adapted from a previously published inhibitor-classification system. Its purpose is to provide a transparent structure for judging the maturity of the evidence supporting a particular inhibitor formulation.

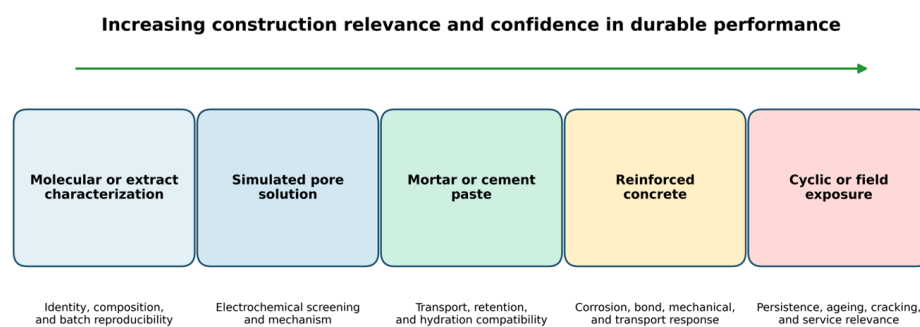


Figure 1. Original evidence hierarchy proposed by the authors for translating a green or bio-based inhibitor from chemical screening to construction-relevant durability validation. The framework was developed through the critical synthesis of the methodological and application requirements discussed in Refs. [4,5,9,10,18,20–23,27,28,45]. The arrow indicates cumulative progression toward increasing construction relevance and confidence in durable performance. Colors distinguish the successive validation domains only and do not represent quantitative performance.

The framework addresses three limitations of conventional literature comparisons. First, it prevents a high inhibition efficiency obtained during short-term testing in a simulated pore solution from being treated as equivalent to durable protection in mortar or concrete. Second, it requires the electrochemical response to be supported progressively by chemical characterization, surface evidence, cement compatibility, transport, mechanical performance, and long-term exposure. Third, it separates evidence of corrosion control from evidence of environmental safety, formulation reproducibility, scalability, and field applicability. Assignment to a level is therefore based on the complete evidence available for an inhibitor system rather than on its single highest reported efficiency.

4.2. Electrochemical Evaluation Techniques

Electrochemical measurements dominate the inhibitor literature because they are sensitive to changes in charge transfer, passive-film behavior, and corrosion kinetics. However, each technique addresses a different question, and none is sufficient alone. Open-circuit potential (OCP) follows the mixed potential of the steel but does not directly measure corrosion rate. A more noble potential after inhibitor addition may indicate passivation, yet oxygen availability, moisture, reference-electrode location, and junction potentials can produce similar shifts. Conversely, active corrosion can occur without an extreme potential when macro-cell coupling or heterogeneous moisture is present [3–5,27,28]. Half-cell potential mapping is therefore valuable for locating electrochemically distinct regions in concrete, but probability criteria should be applied with the limitations specified in ASTM C876-22b [33].

Linear polarization resistance (LPR) provides a non-destructive estimate of corrosion current through the Stern–Geary relationship [34]. Its reliability depends on sufficiently small polarization, stable potential, correct compensation for ohmic drop, a defensible Stern–Geary constant, and knowledge of the polarized reinforcement area. These issues become particularly important in concrete because current spreads through a resistive and geometrically complex electrolyte. Foundational work on laboratory and on-site monitoring showed the importance of current confinement and interpretation of corrosion-rate ranges [35]. Potentiodynamic polarization provides anodic and cathodic branches, corrosion potential, corrosion current, and qualitative classification of inhibitor action, but scan range and rate can disturb the passive film. ASTM G59-23 and ASTM G102-23 provide relevant principles for polarization resistance and corrosion-rate calculations [36,37].

Electrochemical impedance spectroscopy (EIS) is particularly informative for bio-based systems because the evolution of solution resistance, surface-film resistance, charge-transfer

resistance, and non-ideal capacitance can be followed without large potential excursions. Nevertheless, spectra from reinforced concrete may contain overlapping contributions from the pore network, interfacial zone, passive or inhibitor film, corrosion products, and diffusion. Equivalent circuits are not unique, and a visually acceptable fit does not establish a physical mechanism. Ribeiro and Abrantes emphasized the need to relate impedance features to physically meaningful processes in reinforced concrete [38]. In inhibitor studies, increased resistance and reduced effective capacitance should therefore be supported by time dependence, fit uncertainty, surface analysis, and consistent polarization or LPR results [11–17,19,20,23,43–50].

Standards designed for concrete corrosion provide an additional bridge between academic screening and application. ASTM G109-23 evaluates the effect of admixtures on embedded reinforcement under chloride exposure, whereas ASTM G180-23 addresses corrosion-inhibiting admixtures through polarization resistance in cementitious slurries [39,40]. The RILEM TC 154-EMC recommendation further details polarization-resistance measurements on large concrete members, including current confinement and the definition of the polarized area [41], while embedded probes enable time-resolved monitoring of potential, resistivity, oxygen availability, and corrosion rate at selected locations [42]. These procedures cannot capture every bio-based formulation, particularly coatings or migrating systems, but they provide common points for specimen geometry, exposure, controls, and reporting. Recent critical reviews likewise call for multiscale, multi-technique evaluation rather than isolated efficiency values [29]. Table 3 summarizes the principal techniques and the complementary evidence required for defensible interpretation.

Table 3. Principal techniques used to evaluate bio-based and naturally derived corrosion inhibitors for reinforced concrete and the evidence required for interpretation.

Technique	Primary Output	Main Contribution	Key Limitation	Recommended Complementary Evidence
OCP/half-cell potential	E _{corr} and spatial potential gradients	Tracks potential evolution and identifies electrochemically distinct areas	Does not directly measure corrosion rate; affected by oxygen, moisture, resistivity, and reference position	LPR, resistivity, moisture state, and potential mapping [33]
LPR	R _p and estimated i _{corr}	Non-destructive time-dependent corrosion-rate estimate	Requires Stern–Geary constant, ohmic-drop control, and defined polarized area	Polarization or mass loss; current confinement [34–37]
Potentiodynamic polarization	E _{corr} , i _{corr} , anodic, and cathodic slopes	Estimates efficiency and supports anodic, cathodic, or mixed classification	Scan can perturb passive or inhibitor films; result depends on range and scan rate	EIS, OCP history, and post-test surface analysis [11–20,36]
EIS	R _s , film and charge-transfer resistance, CPE/capacitance	Separates time-dependent interfacial and transport contributions	Equivalent circuits are non-unique and overlapping processes complicate interpretation	Fit uncertainty, time series, polarization, and XPS/SEM [11–17,23,38]
Mass loss	Cumulative metal loss and corrosion rate	Direct integral measure over the exposure period	Cleaning can remove substrate or retain products; insensitive to temporal changes	Electrochemical monitoring, replicate blanks, and surface profilometry [16]
Surface/chemical analysis	Composition, oxidation state, functional groups, morphology, roughness	Links inhibitor chemistry with interfacial film and corrosion products	A single spectrum or micrograph rarely proves causation or protection	Electrochemical response plus controls and quantitative chemical fingerprint [10–17,43,44]
Concrete-scale exposure	Corrosion response, transport, bond, strength, and cracking	Provides the strongest construction relevance	Long duration, specimen variability, and difficulty isolating mechanisms	Cyclic exposure, replicated controls, absolute corrosion rate, and standards [18,20–22,33,39–42]

4.3. Chemical and Surface Characterization of Protective Films

The composition of a bio-based inhibitor must be characterized before its interfacial mechanism can be interpreted. For plant extracts and biomass residues, extraction yield, solvent, pH, total phenolic or flavonoid content, chromatographic fingerprint, and batch-to-batch variability are more informative than botanical name alone. GC–MS, HPLC and LC–MS can identify or quantify candidate constituents, while FTIR and Raman spectroscopy identify functional groups and changes associated with extraction or adsorption [10–14,24–26,43–49]. Recent critical assessments emphasize that “green” origin does not by itself establish reproducibility, low toxicity, or environmental advantage; the extraction route, solvent burden, composition, and safety data must also be reported [30]. These techniques are complementary: a GC–MS library match does not prove that the compound controls inhibition, and a shifted FTIR band is not by itself evidence of chemisorption.

Surface-sensitive techniques are needed to connect solution chemistry with the steel interface. XPS can identify iron oxidation states, organic heteroatoms, and changes consistent with Fe–O, Fe–N, or metal–organic bonding. This approach supported a chemically bonded layer for glutamic acid and adsorption-related protection for licorice extract [15,44]. SEM provides direct comparison of surface damage and deposit morphology, whereas EDS supplies elemental context; neither technique alone quantifies film adhesion or electrochemical protection. AFM and profilometry can quantify roughness, while contact-angle measurements help assess changes in surface wettability. Cross-sectional microscopy is especially useful for coatings because it reveals thickness, defects, and interfacial continuity [11–17,21–23,43,44]. Recent protein-based work on ovalbumin combined electrochemical, morphological, and theoretical analyses, illustrating the value—and the remaining solution-to-concrete translation gap—of a multi-method design [51].

Mechanistic interpretation should connect how the inhibitor is delivered, how its active species reach the steel–concrete interface, and which interfacial process is modified. Bio-based compounds may be incorporated as admixtures, applied as migrating treatments or immobilized in coatings; after transport through the pore network, oxygen-, nitrogen- and sulfur-containing groups can interact with iron oxides or exposed metal sites, while larger organic fractions may restrict the ingress of chloride, water and oxygen. Depending on composition, these effects can reduce anodic iron dissolution, hinder the cathodic oxygen-reduction reaction, and/or increase the resistance of the interfacial layer [10–17,19–23,29–31,43–51]. Figure 2 integrates these coupled routes at the steel–concrete interface. It is a mechanistic synthesis rather than a universal pathway: adsorption, kinetic suppression, and transport limitation must be demonstrated for each formulation with complementary electrochemical, surface-chemical, and cement-compatibility evidence.

4.4. Quantitative Comparison of Reported Inhibition Efficiencies

Inhibition efficiency is commonly calculated from corrosion current, polarization resistance, charge-transfer resistance, or mass loss. Values obtained from these quantities are related but not interchangeable. Efficiency calculated from EIS may emphasize a particular fitted resistance, whereas polarization integrates the response obtained under an imposed potential scan and gravimetric measurements represent cumulative material loss. The reference condition also matters: a severely corroding blank can produce a high relative efficiency even when the residual corrosion rate remains unacceptable. Consequently, both the percentage and the underlying measured quantity should be reported [9,10,34,35,38].

Delivery and protection mechanisms of bio-based corrosion inhibitors at the steel-concrete interface

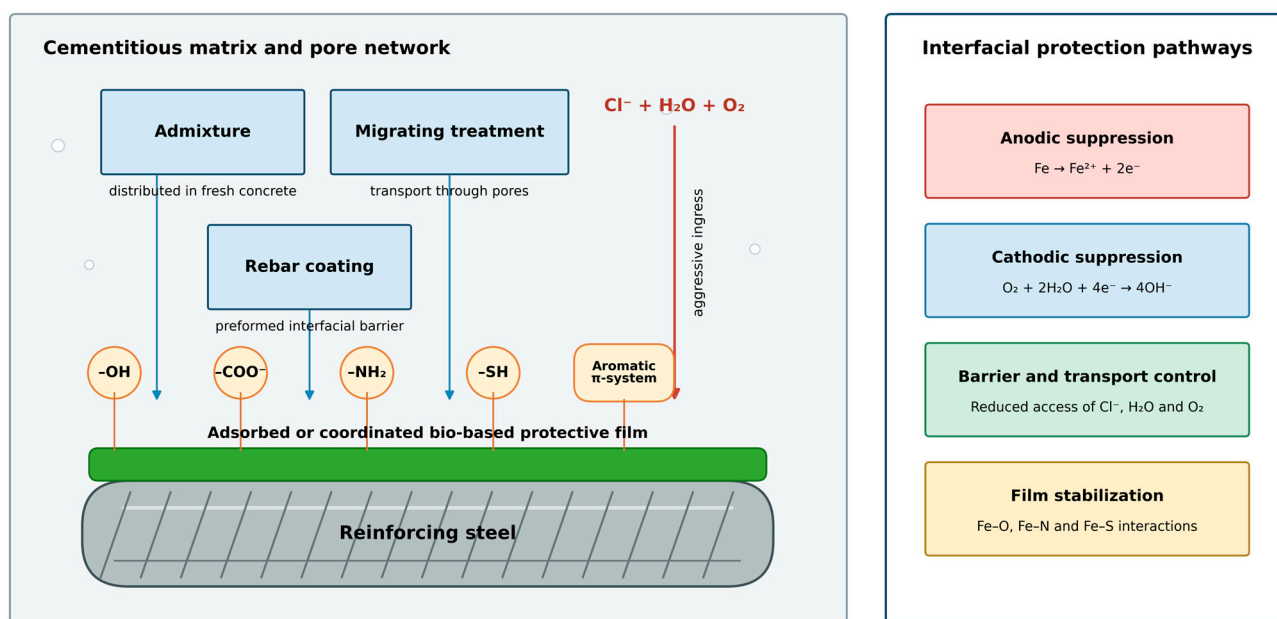


Figure 2. Mechanistic synthesis of green and bio-based inhibitor delivery and protection at the steel-concrete interface. Depending on the formulation, active species may be introduced as admixtures, migrating treatments or coatings; protection may arise from adsorption or co-ordination, modification of anodic and cathodic kinetics, and restriction of aggressive-species transport [10–23,29–31,43–51]. The scheme is an original synthesis; not every pathway applies to every inhibitor family. The circles identify representative functional groups and active chemical motifs involved in adsorption or coordination at the steel surface.

Reported inhibition efficiencies must be interpreted according to their measurement basis and the experimental conditions of the original studies. Potentiodynamic polarization, EIS, LPR, and mass-loss measurements represent related but non-equivalent electrochemical or physical responses. Corrosion current density obtained from potentiodynamic polarization reflects polarization-derived corrosion kinetics; charge-transfer resistance obtained from EIS describes the resistance of the steel-electrolyte interface to the charge-transfer process; polarization resistance obtained from LPR provides a non-destructive estimate of corrosion activity; and mass loss represents cumulative material loss over a specified exposure period.

Consequently, efficiencies derived from corrosion current density, charge-transfer resistance, polarization resistance, and mass loss were separated into distinct methodological categories and were not treated as interchangeable values. The studies represented in Figure 3 also differ in initial steel condition, electrolyte or simulated pore-solution composition, pH, chloride concentration, inhibitor dosage, experimental temperature, and exposure time, as specified in the corresponding original publications [15,16,18,52]. These differences prevent direct numerical equivalence among the reported efficiencies.

Figure 3 therefore groups the reported values according to measurement basis. Comparisons are made only within the corresponding methodological category and are intended to illustrate general trends and method-dependent responses rather than establish an absolute ranking of inhibitor performance. Numerical values were retained according to the calculation procedure reported in each original publication, except where recalculation from published control and inhibited data is explicitly identified.

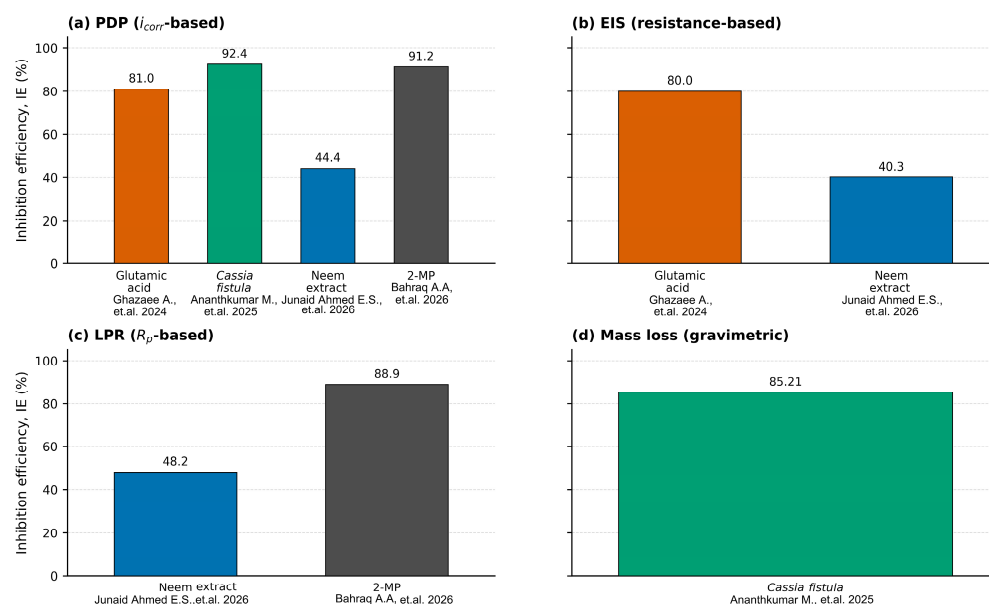


Figure 3. Inhibition efficiencies grouped according to measurement basis: (a) corrosion-current-density-based efficiency obtained by potentiodynamic polarization; (b) resistance-based efficiency obtained by electrochemical impedance spectroscopy; (c) polarization-resistance-based efficiency obtained by linear polarization resistance; and (d) gravimetric efficiency obtained by mass loss [15,16,18,52]. Results presented in different panels represent non-equivalent electrochemical or physical responses and should be interpreted only within their corresponding methodological categories. The figure illustrates general trends and method-dependent responses rather than an absolute cross-method ranking. Values were retained as reported in the original studies, except for the neem values, which were recalculated from the published control and inhibited data in Ref. [18]. The 2-mercaptopyrimidine series is retained only as a low-toxicity organic comparator.

Inhibition efficiency was interpreted according to the parameter employed in each original study. For potentiodynamic polarization, the efficiency based on corrosion current density was calculated as follows:

$$IE_{i_{corr}}(\%) = \frac{i_{corr,0} - i_{corr,inh}}{i_{corr,0}} \times 100 \quad (1)$$

For EIS and LPR, the resistance-based inhibition efficiency was calculated as follows:

$$IE_R(\%) = \frac{R_{inh} - R_0}{R_{inh}} \times 100 \quad (2)$$

In Equation (2), R represents the charge-transfer resistance, R_{ct} , for EIS or the polarization resistance, R_p , for LPR. For mass-loss measurements, the gravimetric inhibition efficiency was calculated as follows:

$$IE_{ML}(\%) = \frac{CR_0 - CR_{inh}}{CR_0} \times 100 \quad (3)$$

In Equation (3), CR represents the gravimetric corrosion rate. Subscripts 0 and inh denote the uninhibited control and inhibited conditions, respectively.

Replicate numbers, standard deviations, and error bars were not consistently reported for all datasets represented in Figure 3. Accordingly, no missing uncertainty values were inferred or reconstructed retrospectively. The plotted efficiencies should therefore be interpreted as descriptive results obtained under the specific experimental conditions of the corresponding original studies.

The technique-stratified comparison also exposes the scarcity of directly comparable concrete-scale data. For neem-modified reinforced concrete, efficiencies calculated here from the reported control and 29 mL results are approximately 44.4% from corrosion current, 48.2% from polarization resistance, and 40.3% from steel resistance obtained by EIS [18]. These values are internally consistent but substantially below several optimized solution-scale maxima, which reinforces the importance of transport, cement interaction, and specimen geometry. The 2-mercaptopyrimidine results are retained in Figure 3 as a recent low-toxicity organic comparator because the study reports closely matched LPR and PDP efficiencies; they are not treated as evidence for a bio-derived inhibitor [52]. Every numerical comparison should still report inhibitor identity and dose, electrolyte composition, chloride concentration, pH, steel preparation, exposure duration, calculation equation, replicates, and uncertainty [9–12,18,24–29,33–42].

4.5. Structure–Function and Application Matrix

A chemically informative classification of bio-based and naturally derived inhibitors should connect active constituents and functional groups with the corresponding protection mechanism, application route, and evidence scale. Botanical or feedstock origin alone is insufficient because chemically different extracts may contain overlapping phenolic, carboxylate, amine, hydroxyl, sulfur-containing, peptide, or macromolecular motifs. Conversely, materials obtained from the same biological source may differ substantially in composition and inhibition behavior because of extraction, purification, concentration, and storage conditions. Table 4 therefore complements the source-based organization presented in Section 3 by grouping inhibitor systems according to dominant active motifs and structure–function relationships. Each family is supported by studies spanning simulated pore solution, mortar, reinforced concrete, coating, or migration configurations [9,10,24–26,29,30]. Table 4 therefore synthesizes recurrent structure–function relationships without assigning one row to each article. Each family is supported by multiple studies spanning simulated pore solution, mortar, reinforced concrete, and coating configurations.

Table 4. Active-component, structure–function, and application matrix for major families of bio-based and naturally derived corrosion inhibitors relevant to reinforced concrete.

Bio-Based Family	Dominant Active Motifs	Representative Sources, Formulations and Validation Scale	Principal Protection Pathway	Advantages	Limitations	Representative References
Extracts and polyphenol-rich systems	Phenolic –OH, carboxylates, carbonyls, aromatic π systems and, depending on the source, N/S heteroatoms	Noni, conifer cone, Bambusa, Ricinus, licorice, Urtica, green tea, Cymbopogon, Phyllanthus, and Rhizophora; tested in simulated pore solution, mortar and reinforced concrete	Competitive adsorption, mixed anodic/cathodic suppression, passive-film stabilization, and hydrophobic or chelating barrier formation	Renewable feedstocks; multiple adsorption sites; potential use of local or residual biomass	Composition and efficiency vary with extraction, season, and batch; active constituents are not always quantified; possible cement interaction	[24–26,43–49,53–62]
Polysaccharides, mucilages and natural gums	Hydroxyl, carboxyl, ether and glycosidic groups in macromolecular chains	Cactus mucilage, brown seaweed polysaccharides, guar gum and nopal slime; tested in alkaline solution, mortar, embedded steel, and protective coatings	Multisite adsorption, viscous or polymeric film formation, pore blocking, and reduced transport of aggressive ions	Abundant and biodegradable; strong surface coverage; compatible with coating and admixture routes	Viscosity and molecular-weight distribution affect transport; water sensitivity, biodegradation, and film persistence require evaluation	[31,63–66]

Table 4. Cont.

Bio-Based Family	Dominant Active Motifs	Representative Sources, Formulations and Validation Scale	Principal Protection Pathway	Advantages	Limitations	Representative References
Amino acids, proteins and other biomolecules	Amino, carboxyl, peptide, amide, thiol and heteroatom-bearing side chains	Glutamic acid, serine, cysteine, ovalbumin, gluten and mussel adhesive protein; tested in pore solution, mortar, migrating treatments, and nanocomposite films	Electrostatic attraction and Fe coordination, anodic-site blocking, self-assembled or cross-linked films and, for proteins, multidentate interfacial adhesion	More interpretable chemistry than crude extracts; tunable functionality; potential synergism and self-healing behavior	pH-dependent speciation; calcium binding; hydrolysis or denaturation; cost, allergenicity, and biological stability may be relevant	[15,17,19,20,50,51, 67–69]
Bio-derived organic acids and chelating molecules	Carboxylate, hydroxyl, phosphate/phytate and enediol groups	Glutamate, amide-based amino acids, phytate and L-ascorbic acid; tested in pore solution and chloride-contaminated mortar	Surface complexation, competitive chloride adsorption, oxide-film modification, and metal-ion chelation	Defined molecular identity; concentration–response relationships can be reproduced; amenable to mechanistic modelling	Over-chelation or excessive dosage can destabilize passivity or alter hydration; performance is sensitive to pH and Ca ²⁺	[15,20,50,70,71]
Waste-derived extracts and bio-based coatings	Concentrated polyphenols, proteins, polysaccharides and oxygenated groups incorporated into films or hybrid carriers	Waste Platanus hydrolysates, plant-extract, soy and cactus-mucilage coatings; tested in pore solution, coated reinforcement, mortar, and concrete	Adsorption combined with barrier protection, controlled availability of active fractions and reduced electrolyte access at the steel surface	Valorizes residues; enables higher active-fraction concentration; adaptable to coating or controlled-release strategies	Processing energy and solvent demand; coating defects, abrasion, bond, and alkaline ageing must be demonstrated	[12,21–23,61,63,67,72–74]
Microbial and biofilm-mediated systems	Cell surfaces, extracellular polymeric substances, carbonate precipitation and biologically generated nitrite	Bacillus subtilis in bagasse, nitrite-producing bacteria, nitrate-reducing CaCO ₃ -precipitating bacteria and biofilm-forming isolates; tested in mortar and concrete	Pore densification, crack filling, local chemical modification, oxygen consumption, and/or biologically generated inhibiting species	Potentially active and self-sustaining protection; combines corrosion control with microstructural densification or self-healing	Viability, nutrients, spatial uniformity and reproducibility are difficult to control; long-term ecological and durability data remain limited	[75–78]

The matrix highlights two complementary trends. Low-molecular-weight compounds such as amino acids, ascorbate, and phytate offer comparatively well-defined chemistry and facilitate mechanistic interpretation, but their ionization, calcium complexation, and retention are strongly dependent on pore-solution composition [15,20,50,70,71]. In contrast, plant extracts, gums, proteins and biomass hydrolysates can provide multidentate adsorption and barrier formation through several functional groups, yet their composition is more sensitive to species, harvest conditions, extraction route and batch variability [24–26,30,53–69,72–74]. Microbial approaches add active mineralization or nitrite-generating functions, although viability, nutrient availability, uniform distribution, and long-term ecological behavior introduce a different set of control variables [75–78].

For multicomponent extracts, assignment to an active-component category was based on the dominant chemical families or functional groups identified by the original study. When the active fraction was not chemically resolved, the mechanism was described as proposed rather than definitively assigned to a single constituent. Reported inhibition performance was attributed to the complete process-defined formulation, not to an individual molecule, unless fractionation, compositional analysis, or testing of isolated compounds provided direct supporting evidence.

4.6. Inhibitor Delivery, Transport, and Compatibility with Cementitious Materials

A technically successful inhibitor must protect the steel without degrading the host material. Organic molecules can adsorb on cement grains, chelate calcium, delay silicate hydration, entrain air, alter rheology, or modify pore structure. These effects are

concentration-dependent and may be beneficial, neutral or harmful. Measurements should therefore include setting time, heat evolution or chemically bound water, workability, air content, compressive and tensile strength, sorptivity, electrical resistivity and chloride transport. For surface-applied or migrating formulations, penetration depth and retained concentration are equally important [9,10,18,20–22,45]. Recent reviews of polymeric and eco-friendly systems similarly identify inconsistent compatibility testing and limited long-term data as major barriers to application [31].

Reinforcement coatings require additional evaluation of adhesion, abrasion resistance, holiday or defect tolerance, alkaline ageing, and steel–concrete bond. Soy-protein and soy-protein/corn-derived polyol coatings have been assessed not only electrochemically but also through abrasion and bond-related measurements [21,22]. This broader framework is important because a continuous laboratory coating may be damaged during transport, cage fabrication, or concrete placement. Similarly, an admixture that increases polarization resistance but reduces bond or produces excessive retardation cannot be judged solely by its corrosion efficiency.

The interaction with supplementary cementitious materials also deserves attention. Blended binders change alkalinity, calcium availability, chloride binding, pore solution chemistry, and electrical resistivity; these changes can modify inhibitor speciation and transport. Migration studies involving ordinary Portland cement and blended concrete already indicate that cement composition affects delivery of amino-acid-based inhibitors [20]. Future comparisons should therefore avoid assuming that performance in one binder system is universal.

The effective concentration at the reinforcement level may differ substantially from the nominal inhibitor dosage introduced into a solution or cementitious mixture. In mortar and concrete, inhibitor molecules can be adsorbed by calcium-silicate-hydrate and other cement hydrates, interact with dissolved calcium or aluminum species, precipitate or lose solubility under highly alkaline conditions, undergo chemical transformation during hydration or carbonation, or become physically retained within the pore network. Molecular size, ionic charge, hydrophilicity, pore connectivity, degree of saturation, chloride binding, carbonation state, and cracking can therefore reduce, delay, or spatially redistribute the active fraction reaching the steel–concrete interface. Nominal dosage should consequently not be considered equivalent to the effective interfacial concentration.

The inhibitor-delivery route also determines the relevant transport mechanism and dosage basis. An inhibitor incorporated during mixing is initially distributed throughout the fresh matrix, but part of the active material may be adsorbed, chemically bound, precipitated, or immobilized during cement hydration before corrosion initiates. Its practical dosage must therefore balance corrosion control against possible effects on setting, workability, air content, hydration, porosity, strength, electrical resistivity, and chloride transport. By contrast, a surface-applied or migrating inhibitor must penetrate hardened concrete through capillary absorption, diffusion, moisture-assisted transport, or concentration gradients. Its effectiveness depends on surface condition, moisture content, cover depth, cracking, curing history, carbonation, pore connectivity, and competing ions. Dosages and efficiencies reported for admixed and surface-applied systems are therefore not directly comparable.

The available evidence should accordingly be interpreted at three distinct application scales. Chemical inhibition potential refers to short-term electrochemical or gravimetric performance in a controlled simulated pore solution. Intermediate-scale performance requires confirmation in cement paste, mortar, or reinforced-concrete specimens, including evidence of matrix compatibility, transport or availability of the inhibitor, and corrosion control under cement-imposed restrictions. Long-term protection requires a persistent reduction in corrosion rate under concrete-relevant chloride or carbonation exposure,

preferably including realistic cover, wet–dry cycling, cracking, leaching, and ageing. High efficiency in a short-term solution test should therefore not be interpreted as proof of permanent concrete protection. Most available studies report the nominal concentration initially added, whereas direct measurements of inhibitor concentration at reinforcement depth, concentration profiles, chloride profiles, time-dependent corrosion rate, and long-term retention remain scarce. The absence of these data represents an important limitation in assessing practical readiness.

4.7. Long-Term Durability and Exposure Conditions

Most studies remain too short to establish durability. Exposures of hours or days can identify rapid adsorption but cannot resolve desorption, chemical oxidation, hydrolysis, biodegradation, microbial consumption, leaching, or progressive immobilization by cement hydrates. Even when resistance increases over 168 h, as reported for *Fatsia japonica* extract [11], this period is short relative to infrastructure service life. Concrete-scale neem results are a useful step beyond homogeneous electrolyte screening, but they still require replication under longer cyclic exposures and explicit assessment of variability [18]. Long-term testing should track absolute corrosion rate and uncertainty, rather than only retention of a high relative efficiency.

Where possible, time-dependent corrosion measurements should be evaluated together with inhibitor concentration at reinforcement depth, chloride profiles, leaching, and post-exposure retention to determine whether protection results from persistent interfacial availability rather than a transient initial response.

Moisture and oxygen deserve particular control because they jointly determine cathodic kinetics and ionic connectivity. Recent steel–concrete interface research shows that chloride, saturation state, and dissolved oxygen act interdependently in macro-voids [5]. A bio-based film that performs well during continuous immersion may crack, desorb, or redistribute during wet–dry cycling. Carbonation additionally lowers pH and changes molecular ionization, iron-oxide stability, and calcium interactions [20,27,28,50]. The most informative durability protocols should therefore combine chloride exposure, carbonation where relevant, cyclic moisture, temperature variation, and realistic oxygen access.

Cracking is another decisive but underrepresented condition. Cracks shorten the transport path and create localized cells that cannot be reproduced in a homogeneous pore solution. For migrating inhibitors, the question is whether sufficient active material reaches the steel after cracking; for coatings, it is whether protection persists at mechanical damage sites. Hybrid systems that combine chloride capture and controlled release, such as alanine-intercalated layered double hydroxides, offer a rational response but still require validation of release kinetics, hydration effects, and long-term retention in concrete [23].

4.8. Critical Appraisal and Minimum Evidence Requirements

The four-level hierarchy was operationalized using the highest level for which an inhibitor system satisfied all essential requirements, rather than the level associated with its single highest reported inhibition efficiency. The unit of classification was the inhibitor system, defined by its active formulation and delivery route. When several publications examined the same formulation or closely related versions of it, the complete body of evidence was considered jointly. Advancement required cumulative evidence; therefore, evidence assigned to a higher level also had to retain the essential requirements established at the preceding levels.

The criteria combine experimental scale, duration, corrosion response, independent mechanistic confirmation, cementitious-material compatibility, transport, reproducibility, environmental safety, and field relevance. Quantitative inhibition efficiency alone was not

used as a universal progression threshold because efficiencies calculated from i_{corr} , R_p , R_{ct} , and mass loss represent non-equivalent responses. Instead, progression required a statistically supported reduction in an absolute corrosion parameter relative to an appropriate uninhibited control, together with the level-specific evidence summarized in Table 5.

Table 5. Operational criteria proposed for assigning inhibitor systems to the four levels of evidentiary maturity.

Evidence Level	Experimental Scope	Essential Measurable Criteria	Additional Evidence Required	Interpretation
Level I: Controlled electrochemical screening	Defined simulated concrete pore solution or alkaline electrolyte; short-term testing	Clearly reported inhibitor dose, pH, chloride concentration, temperature, exposure time, steel preparation, and uninhibited control; statistically supported reduction in i_{corr} , corrosion rate, or mass loss, or corresponding increase in R_p or R_{ct} ; preferably ≥ 3 independent specimens or measurements	At least one validated electrochemical or gravimetric method and a concentration-response assessment	Evidence of chemical inhibition potential under controlled conditions only
Level II: Mechanistic and reproducible laboratory validation	Defined alkaline or carbonated solution with complementary testing	Level I requirements; inhibition response confirmed by at least two complementary techniques or measurement times; reported dispersion or uncertainty; protection maintained during the stated laboratory exposure; chemically defined formulation or reproducible extract fingerprint	Direct surface or chemical evidence, such as XPS, FTIR, Raman spectroscopy, SEM/EDS, AFM, or chromatography; mechanistic interpretation consistent with electrochemical results	Evidence that the observed response is reproducible and supported by an interfacial mechanism, but not yet proof of concrete-scale performance
Level III: Cementitious-material and durability validation	Cement paste, mortar, reinforced concrete, or reinforcement coating tested under cementitious exposure	Level II requirements; corrosion reduction demonstrated in embedded steel; inhibitor delivery or availability at reinforcement depth addressed; reference and replicated specimens included; performance evaluated over a concrete-relevant exposure period or accelerated cyclic regime	Setting-time variation preferably within ± 60 min of the control and 28-day compressive-strength retention preferably $\geq 90\%$, unless another project-specific acceptance criterion is justified; evaluation of workability, bond, resistivity, porosity, or chloride transport as applicable; at least three replicate specimens per principal condition	Evidence of intermediate-scale performance and compatibility under matrix-imposed transport and chemical restrictions
Level IV: Field-relevant and environmental validation	Large-scale element, pilot application, natural exposure, or monitored field trial	Level III requirements; persistent corrosion control under realistic cover, cracking, wet-dry, chloride, carbonation, ageing, or leaching conditions; predefined acceptance criteria; reproducibility across at least two independent batches and preferably more than one laboratory or exposure site	Documented formulation quality control; evidence concerning toxicity, leaching, biodegradability or persistence, and aquatic ecotoxicity where relevant; comparative environmental or life-cycle assessment; scale-up and application feasibility	Evidence supporting long-term protection and application readiness; not equivalent to universal certification

The numerical values in Table 5 are proposed screening benchmarks rather than universal acceptance limits. The recommended $\geq 90\%$ strength retention is intended to limit adverse effects on the host material, while the ± 60 min setting-time criterion identifies substantial retardation or acceleration requiring formulation-specific justification. More restrictive project-, regulatory-, or standard-based criteria should prevail when applicable. No minimum inhibition-efficiency percentage was imposed across all levels because relative efficiencies depend on the measurement basis, initial corrosion condition, exposure period, and reference state.

Borderline cases were assigned conservatively to the lower evidence level. If a study met the experimental-scale requirement of a higher level but did not report an essential criterion—such as replicate number, uncertainty, cement compatibility, exposure duration, inhibitor transport, or effective availability at reinforcement depth—it was not advanced solely on the basis of a favorable inhibition-efficiency value. Information identified as

“not reported” was treated as missing evidence rather than as evidence that the corresponding criterion had been satisfied. When multiple studies addressed the same inhibitor family but employed different extraction procedures, compositions, concentrations, or delivery routes, they were evaluated as separate systems. Evidence from different publications was combined only when the inhibitor formulation and its application route were sufficiently comparable.

The assigned level represents the highest evidentiary stage supported by the complete information reported for each inhibitor system. It should not be interpreted as a ranking of inhibition efficiency or intrinsic chemical performance. Thus, a formulation evaluated in mortar or concrete was not automatically assigned to Level III when essential compatibility, replication, transport, or time-dependent corrosion information was absent. Similarly, no system was assigned to Level IV solely because it was tested in a large specimen or during an extended exposure; field relevance, reproducibility, formulation quality control, persistent corrosion protection, and environmental-safety evidence were also required.

Within this hierarchy, solution-only studies were treated as evidence of chemical inhibition potential, whereas claims of intermediate-scale performance or long-term protection required cementitious-matrix testing and time-dependent corrosion assessment under relevant exposure conditions.

Application of the operational criteria to the 49 inhibitor-focused primary publications showed that 5 studies (10.2%) corresponded to Level I, 17 (34.7%) to Level II, and 27 (55.1%) to Level III. No study or sufficiently defined inhibitor system fulfilled all Level IV requirements. Although several studies included mortar, reinforced concrete, coatings, transport assessment, or prolonged laboratory exposure, none combined long-term field validation, independent reproducibility, formulation quality control, persistent corrosion protection, and comprehensive environmental-safety evidence.

For future studies, a minimum evidence package should include the following: (i) verified identity and process-defined composition; (ii) a blank, a dosage series and, where possible, a conventional benchmark; (iii) absolute electrochemical or mass-loss data with replicates, dispersion and uncertainty; (iv) at least one independent surface or chemical method; (v) cement compatibility and transport assessment; and (vi) time-dependent testing under concrete-relevant exposure. Molecular modelling can help identify adsorption sites and formulate hypotheses, as shown in recent integrated experimental–computational work [51,52], but it cannot replace chemical identification, measured interfacial composition, or concrete-scale validation. Environmental claims require toxicity, biodegradation, extraction-energy, solvent-recovery, and life-cycle information [9,10,24–26,30,31]. Adopting this framework would shift the field from reporting isolated maximum efficiencies toward demonstrating reproducible and durable protection of reinforced concrete.

5. Discussion

The available literature establishes that green and bio-based compounds can alter the electrochemical response of reinforcing steel and, in several cases, substantially reduce corrosion under controlled alkaline and chloride-containing conditions. The central issue is no longer whether biological molecules can inhibit corrosion, but whether the reported protection is chemically reproducible, compatible with cementitious materials, persistent under realistic exposure, and scalable to construction practice. The evidence assembled in Sections 3 and 4 supports a cautiously positive assessment: strong laboratory responses are recurrent, whereas durable concrete-scale validation remains comparatively limited [11–23,29–31,43–51,53–78].

5.1. Integrated Interpretation of the Available Evidence

Plant extracts, polysaccharides, amino acids, proteins, waste-derived fractions, and microbial systems act through partially overlapping processes, including competitive adsorption, coordination with iron or iron oxides, passive-film stabilization, modification of anodic and cathodic kinetics, and restriction of aggressive-species transport [10–17,19–23,43–50,53–78]. This mechanistic overlap explains why chemically dissimilar formulations can produce comparable electrochemical responses. It also prevents a simple ranking based on botanical origin. Performance is controlled by the concentration and accessibility of active functional groups, their stability at high pH, their interaction with cement hydrates, and their ability to remain at the steel surface during chloride ingress, wetting–drying, and ageing.

The most convincing studies combine changes in corrosion current or polarization resistance with impedance evolution, mass loss and evidence of an altered steel surface [11–17,19,29–31,43–51]. Agreement among these independent domains strengthens a protection claim, whereas a single high inhibition-efficiency value only demonstrates a response under the selected test conditions. The current evidence therefore supports the technical feasibility of several bio-based families, but does not demonstrate universal superiority over conventional inhibitors or equivalence among products described under the same broad label.

5.2. Comparability and Interpretation of Reported Performance

The numerical comparison of inhibition efficiencies remains one of the principal weaknesses of the literature. Reported percentages are derived from corrosion current, polarization resistance, charge-transfer resistance, or mass loss, and each quantity represents a different time scale and physical response [9,10,34–38]. Values obtained in simulated pore solution cannot be directly transferred to mortar or concrete because transport, adsorption by hydrates, electrical resistivity, moisture distribution, and cover depth modify the concentration available at the reinforcement [18,20–22,45]. Even within one technique, differences in steel preparation, chloride concentration, inhibitor dose, exposure period, polarization range, equivalent circuit, and reference condition can produce substantial variation.

Consequently, reported maxima should be interpreted as formulation-specific outcomes rather than intrinsic material constants. Cross-study synthesis is more defensible when it distinguishes test scale, exposure environment, calculation basis, and residual absolute corrosion rate. A formulation that achieves a high relative efficiency against a severely corroding blank may still leave the steel above an acceptable corrosion threshold. Future comparative studies should therefore report the raw electrochemical quantities, uncertainty, replicate number, and blank response in addition to the calculated efficiency [29,33–42].

5.3. Compatibility with Cementitious Materials and Performance Trade-Offs

Protection of reinforcement cannot be optimized independently of the cementitious matrix. Hydroxyl-, carboxylate-, phosphate-, amine-, and peptide-bearing compounds may adsorb on cement grains, complex calcium, alter nucleation and growth of hydration products, entrain air, or change rheology and pore structure. These interactions can delay setting, modify early-age strength, or influence chloride transport even when the electrochemical response at the steel surface is favorable [18,20–22,31,45,68,70,71]. Conversely, macromolecular or microbial formulations may reduce permeability or promote local densification, creating a combined transport and interfacial benefit [63–66,75–78].

The relevant design variable is therefore not the dose that maximizes short-term inhibition in solution, but the concentration range that provides adequate corrosion control without unacceptable effects on hydration, mechanical properties, bond, and durability. For

admixtures, this requires simultaneous evaluation of setting, calorimetry or hydration products, workability, air content, strength, electrical resistivity, and chloride transport. Coatings additionally require adhesion, abrasion resistance, defect tolerance, alkaline ageing, and steel–concrete bond testing [21–23,63,67,74]. These trade-offs should be incorporated into formulation optimization rather than examined only after electrochemical screening.

5.4. Chemical Standardization and Reproducibility

Reproducibility is particularly challenging for plant extracts and biomass-derived products. Species, geographical origin, season, plant part, storage, particle size, extraction solvent, temperature, and extraction time can alter the concentration of phenolics, alkaloids, proteins, sugars, and other active constituents [24–26,30,32,53–62,72,73]. A botanical name and nominal extract concentration are therefore insufficient descriptors. At minimum, studies should report dry-matter yield, extraction conditions, solution pH, concentration basis, storage stability, and a chemical fingerprint obtained with suitable chromatographic or spectroscopic methods.

Standardization does not require complete identification of every constituent, but it should establish measurable attributes linked to performance. Total phenolic or flavonoid content can support batch comparison, while HPLC, LC–MS, or GC–MS profiles can identify marker compounds. Fractionation, controlled recombination, and adsorption studies can then distinguish active constituents from chemically abundant but electrochemically irrelevant species [10–14,24–26,30]. Defined amino acids and organic acids offer greater chemical reproducibility, although their speciation and calcium-binding behavior remain sensitive to pore-solution chemistry [15,20,50,70,71].

5.5. Environmental Performance and Sustainability Claims

Biological origin should not be treated as direct evidence of sustainability. Environmental performance depends on feedstock availability, land or agricultural demand, solvent selection, extraction yield, energy consumption, product stability, required dose, and frequency of application. Waste-derived feedstocks may offer a stronger circular-economy rationale than purpose-grown materials, but processing burdens and variability can offset this advantage [12,24–26,30,32,72–75]. The toxicity of the final formulation, rather than that of the source alone, is also relevant because extraction can concentrate bioactive compounds or introduce residual solvents.

Environmental evaluation should distinguish feedstock origin, hazard, and comparative environmental performance. Feedstock renewability can be verified from the biological or residual source, whereas low toxicity requires evidence concerning the inhibitor, extraction residues, leachates, and transformation products. Demonstrated environmental superiority additionally requires comparison with a technically equivalent reference inhibitor using a consistent functional basis, such as the amount of formulation and associated impacts required to provide a defined reduction in corrosion rate over a specified protection period.

A minimum environmental dataset should include the extraction solvent and recovery route, process yield, relevant toxicity information, biodegradability or persistence, and potential aquatic effects. Where broader sustainability claims are made, water and energy consumption, waste generation, carbon footprint, service-life extension, and life-cycle impacts should also be evaluated. The absence of these data does not demonstrate adverse environmental performance, but it prevents the inhibitor from being classified conclusively as environmentally superior.

Defensible environmental claims require a defined functional unit and comparison with a technically equivalent reference system. Life-cycle assessment following

ISO 14040 and ISO 14044 can identify whether benefits from renewable or residual feedstocks outweigh extraction, purification, transport, and replacement burdens [79,80]. Ready-biodegradability testing provides useful information but should be combined with aquatic toxicity, leaching and service-life considerations [81]. A formulation that requires frequent reapplication or provides shorter protection may have a greater life-cycle burden despite being biodegradable. Environmental assessment should therefore be coupled to demonstrated durability and life extension.

5.6. Technology Readiness and Field Translation

The literature is concentrated at the early stages of technology development: chemical characterization, electrochemical screening, and short-term exposure in simulated pore solutions. Mortar and reinforced-concrete studies provide substantially stronger evidence, yet relatively few formulations have been examined under realistic cover depths, cracked conditions, combined carbonation and chloride exposure, cyclic saturation, temperature changes, or long-term natural exposure [18,20–23,45,53–78]. This imbalance explains why high laboratory efficiency has not yet produced broad construction adoption.

Economic feasibility is also a critical requirement because corrosion-inhibitor applications may involve large volumes of concrete, extensive reinforcement areas, or repeated surface treatment. The relevant cost is not limited to the price of the biological feedstock. It also includes feedstock collection and conditioning, drying, grinding, extraction yield, solvent and water consumption, energy demand, purification or fractionation, solvent recovery, formulation, storage stability, chemical quality control, transportation, dosage, application, and potential reapplication. Waste-derived materials may reduce raw-material costs, but low extraction yield, compositional variability, purification requirements, or short shelf life can offset this apparent advantage.

A direct cost ranking could not be established from the reviewed literature because most studies were conducted at laboratory scale and did not report sufficiently detailed or comparable production-cost data. Reported inhibitor concentrations also use different bases, including mass fraction, volume fraction, solution concentration, or extract volume, and do not correspond to a common construction function. Future techno-economic assessments should therefore normalize costs using application-specific functional units, such as cost per cubic meter of treated concrete for admixed inhibitors, cost per square meter of treated surface for migrating formulations, or cost per unit area or mass of protected reinforcement for coatings. These costs should be evaluated together with achieved corrosion reduction, expected protection duration, maintenance frequency, and service-life extension rather than comparing feedstock price alone.

A staged validation pathway is proposed in Figure 4. Advancement should depend on explicit decision gates rather than on a single performance threshold. Chemical consistency must precede comparative screening; electrochemical activity must be retained in cementitious matrices; compatibility must be demonstrated before prolonged concrete exposure; and field trials should include monitoring, controls, and defined acceptance criteria. Chloride transport measurements, service-life-oriented exposure design and maintenance planning can be aligned with established test and durability frameworks [39–42,82–84]. The pathway is intentionally selective: formulations that cannot meet reproducibility, compatibility, or safety requirements should not progress merely because they show high initial efficiency.

5.7. Research Priorities and Minimum Validation Requirements

Future work should prioritize comparable evidence rather than an increasing number of isolated extract screenings. The principal needs are chemically controlled formulations,

common electrochemical and exposure conditions, concrete-scale dose optimization, long-term cyclic testing, environmental assessment, and pilot validation. Table 6 converts these needs into minimum evidence requirements. This framework is not intended to impose one protocol on every delivery route; admixtures, migrating treatments, coatings, and microbial systems require different supplementary tests. Its purpose is to define a common evidentiary core that permits comparison and supports decisions about further development.

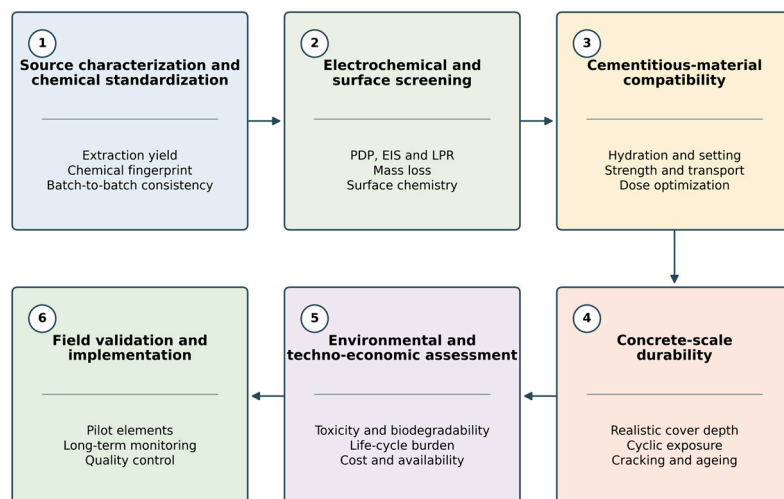


Figure 4. Stage-gated pathway for translating green and bio-based corrosion inhibitors from source characterization to field implementation. Progress requires simultaneous evidence of reproducibility, corrosion protection, cementitious compatibility, environmental acceptability, and persistent performance [29–32,39–42,51,79–84]. Original synthesis developed from the critical appraisal presented in this review. The colors distinguish the successive validation stages and decision domains only; they do not represent a quantitative performance scale or an absolute ranking of inhibitor technologies.

Researchers can use the proposed framework to identify the current evidentiary maturity of a candidate inhibitor and to design the subsequent validation stage before making claims of practical applicability. For example, a system supported exclusively by short-term electrochemical screening should progress toward formulation standardization, independent surface confirmation, and cement-compatibility assessment rather than merely repeating inhibition-efficiency measurements under similar solution conditions. Systems already evaluated in mortar or concrete should subsequently address transport to reinforcement depth, retention, cyclic exposure, mechanical compatibility, environmental safety, and reproducibility.

Practitioners and decision-makers can use the same framework to distinguish preliminary experimental formulations from inhibitor systems supported by concrete-scale durability, environmental, reproducibility, and field evidence. The framework is therefore intended as a decision-support structure for identifying evidence gaps and defining subsequent validation requirements, rather than as an absolute ranking of inhibitor chemistries or commercial products.

The strongest research designs will connect composition, interfacial mechanism, concrete compatibility, persistent corrosion control, and environmental performance within the same formulation. Such integration would allow future reviews and meta-analyses to compare normalized outcomes rather than isolated maxima. It would also clarify where bio-based inhibitors offer their greatest advantage: direct replacement of conventional admixtures, surface-applied maintenance, functional coatings, controlled-release systems, or multifunctional microbial technologies. Until this evidence is available, the most appropriate conclusion is that green and bio-based inhibitors constitute a promis-

ing but heterogeneous technology class whose practical readiness varies substantially among formulations.

Table 6. Critical research gaps and minimum evidence required for the practical development of bio-based and potentially environmentally preferable corrosion inhibitors.

Research Gap	Current Limitation	Recommended Investigation	Minimum Evidence	Expected Contribution
Chemical standardization	Composition varies with source, extraction, and storage	Fingerprint representative batches and quantify marker compounds	Extraction yield, concentration basis, FTIR plus HPLC/LC-MS/GC-MS where applicable [24–26,30,32]	Reproducible formulations and traceable variability
Electrochemical comparability	Different environments, endpoints, and calculation bases	Use common controls and complementary time-resolved techniques	PDP with EIS or LPR, mass loss, absolute corrosion rate, replicates, and uncertainty [29,33–42]	Defensible within- and between-study comparison
Cement compatibility	Electrochemical efficiency is often evaluated separately from concrete properties	Optimize inhibition and matrix performance simultaneously	Setting/hydration, workability, strength, resistivity, porosity, and chloride transport [18,20–22,31,45]	Identification of technically viable dosage ranges
Long-term durability	Short immersion tests dominate	Apply cyclic chloride, carbonation, wet–dry, temperature, and ageing exposures	Time-dependent corrosion monitoring, surface analysis, and post-exposure damage [29,39–42,82]	Evidence of persistent rather than transient protection
Environmental validation	The terms green and sustainable are frequently assumed from origin	Evaluate toxicity, biodegradation, and life-cycle burdens against a functional reference	Defined functional unit, ISO-based LCA, biodegradability, leaching, and toxicity [79–81]	Quantifiable and defensible sustainability claims
Economic feasibility	Production, formulation, application, and maintenance costs are rarely reported and are not normalized to a common functional unit	Conduct laboratory-to-pilot techno-economic assessment and compare with a technically equivalent conventional inhibitor	Feedstock and processing cost, extraction yield, solvent and energy demand, formulation and quality-control cost, application dosage, maintenance frequency, protection duration, and cost per functional unit	Comparable life-cycle cost, identification of economically viable formulations, and improved scale-up decisions
Scale and field translation	Few pilot elements or natural-exposure studies	Progress from mortar to reinforced concrete, structural elements, and monitored field trials	Realistic cover, cracks, controls, service exposure, quality control, and acceptance criteria [39–42,83,84]	Technology-readiness assessment and implementation guidance

6. Conclusions

Green and bio-based corrosion inhibitors constitute a technically promising but heterogeneous group of strategies for protecting steel reinforcement in chloride-contaminated and carbonated cementitious environments. Plant extracts, biomass-derived compounds, amino acids, proteins, polysaccharides, bio-based coatings, and microbial systems can reduce corrosion through adsorption, coordination with the steel or oxide surface, passive-film stabilization, modification of anodic and cathodic reactions, and restriction of aggressive-species transport. The available evidence nevertheless shows that botanical or biological origin alone does not determine performance; protection depends on chemical composition, dosage, delivery route, exposure conditions, and the ability of the active species to reach and remain at the steel–concrete interface.

Biological origin, low toxicity, and demonstrated environmental superiority should therefore be reported as separate attributes. In the absence of toxicity, biodegradability, ecotoxicity, process-energy, carbon-footprint, or life-cycle information, formulations should be described more cautiously as bio-based, plant-derived, naturally derived, or potentially low-toxicity rather than being assumed to be green.

Application of the proposed operational criteria indicates that the available literature remains concentrated at Levels I–III, while no inhibitor system currently satisfies all requirements for Level IV field and environmental validation. Selected formulations have progressed to mortar, reinforced-concrete, coating, or transport assessment, but long-term field performance, independent reproducibility, formulation quality control, and environmental safety have not yet been demonstrated together. Future research should therefore

prioritize concrete compatibility, transport and retention at reinforcement depth, long-term durability, field monitoring, and environmental assessment rather than merely reproducing high short-term inhibition efficiencies in simulated pore solutions.

High inhibition efficiencies reported in simulated pore solutions demonstrate chemical inhibition potential but cannot be interpreted as direct evidence of durable protection in reinforced concrete unless transport to the reinforcement, effective interfacial availability, cement compatibility, retention, and persistent corrosion control have also been demonstrated. Differences among polarization, impedance, linear-polarization-resistance, and mass-loss measurements, together with variations in chloride concentration, alkalinity, exposure time, steel preparation, and calculation basis, limit direct numerical comparison among studies. The most reliable assessments are those that combine complementary electrochemical measurements with chemical and surface characterization, cement-compatibility testing, and time-dependent evaluation in mortar or concrete.

Practical implementation is currently constrained by variability in the composition of natural extracts, incomplete identification of active constituents, inconsistent reporting of extraction and dosage, limited evaluation of cement hydration and mechanical properties, and a shortage of long-term concrete-scale and field studies. Claims of sustainability also require more than renewable origin. Toxicity, biodegradability, solvent and energy demand, feedstock availability, service-life extension, and life-cycle impacts must be evaluated against technically equivalent conventional systems.

Among the technologies examined, chemically defined bio-derived compounds—particularly amino acids, organic acids, and selected protein-derived molecules—currently offer the most favorable balance between inhibition performance, compositional reproducibility, mechanistic interpretation, and formulation control. Bio-based reinforcement coatings are also promising where a continuous barrier can be produced without compromising adhesion, abrasion resistance, or steel-concrete bonds. Hybrid and controlled-release systems may provide the greatest longer-term potential because they can combine chloride capture, regulated inhibitor availability, passive-film stabilization, and interfacial barrier effects. Standardized waste-derived extracts additionally offer an attractive circular-economy pathway, but their practical development depends on chemical fingerprinting, consistent extraction yield, storage stability, and batch-to-batch quality control. Crude plant extracts and microbial systems remain scientifically promising, although their compositional variability, biological stability, transport, and reproducibility currently limit confident field implementation.

Future improvement should focus on process-defined and chemically reproducible formulations, dose optimization in cementitious matrices, direct measurement of transport and retention at reinforcement depth, and long-term testing under chloride, carbonation, cracking, wet-dry cycling, leaching, and ageing. The most advanced candidates should progress through comparative concrete-scale testing, independent or interlaboratory validation, monitored pilot applications, and integrated toxicological, environmental, and techno-economic assessment. Priority should therefore be given to demonstrating persistent corrosion control and service-life extension rather than reporting additional isolated maxima in short-term solution tests. With this integrated evidence, chemically defined inhibitors, durable bio-based coatings, standardized waste-derived formulations, and controlled-release hybrid systems may become viable components of reinforced-concrete durability design and maintenance.

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References

1. Mehta, P.K.; Monteiro, P.J.M. *Concrete: Microstructure, Properties, and Materials*, 4th ed.; McGraw-Hill Education: New York, NY, USA, 2014.
2. Bertolini, L.; Elsener, B.; Pedferri, P.; Redaelli, E.; Polder, R.B. *Corrosion of Steel in Concrete: Prevention, Diagnosis, Repair*, 2nd ed.; Wiley-VCH: Weinheim, Germany, 2013. [\[CrossRef\]](#)
3. Angst, U.; Elsener, B.; Larsen, C.K.; Vennesland, Ø. Critical Chloride Content in Reinforced Concrete—A Review. *Cem. Concr. Res.* **2009**, *39*, 1122–1138. [\[CrossRef\]](#)
4. Angst, U.M.; Geiker, M.R.; Michel, A.; Gehlen, C.; Wong, H.; Isgor, O.B.; Elsener, B.; Hansson, C.M.; François, R.; Hornbostel, K.; et al. The Steel–Concrete Interface. *Mater. Struct.* **2017**, *50*, 143. [\[CrossRef\]](#)
5. Governo, S.; Rossi, E.; Azad, S.; Kaestner, A.; Angst, U. The Interdependent Roles of Chloride, Moisture and Dissolved Oxygen in Macro-Voids at the Steel–Concrete Interface in Corrosion. *Corros. Sci.* **2026**, *265*, 113814. [\[CrossRef\]](#)
6. Hansson, C.M. The Impact of Corrosion on Society. *Metall. Mater. Trans. A* **2011**, *42*, 2952–2962. [\[CrossRef\]](#)
7. ACI Committee 222. *ACI 222R-19: Guide to Protection of Reinforcing Steel in Concrete Against Corrosion*; American Concrete Institute: Farmington Hills, MI, USA, 2019.
8. Elsener, B. *Corrosion Inhibitors for Steel in Concrete: State of the Art Report*; European Federation of Corrosion Publications No. 35; Maney Publishing: London, UK, 2001; 68p.
9. Zomorodian, A.; Behnood, A. Review of Corrosion Inhibitors in Reinforced Concrete: Conventional and Green Materials. *Buildings* **2023**, *13*, 1170. [\[CrossRef\]](#)
10. Casanova, L.; Ceriani, F.; Messinese, E.; Paterlini, L.; Beretta, S.; Bolzoni, F.M.; Brenna, A.; Diamanti, M.V.; Ormellese, M.; Pedferri, M. Recent Advances in the Use of Green Corrosion Inhibitors to Prevent Chloride-Induced Corrosion in Reinforced Concrete. *Materials* **2023**, *16*, 7462. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Wang, Q.; Wu, X.; Zheng, H.; Liu, L.; Zhang, Q.; Zhang, A.; Yan, Z.; Sun, Y.; Li, Z.; Li, X. Evaluation for *Fatsia japonica* Leaves Extract (FJLE) as Green Corrosion Inhibitor for Carbon Steel in Simulated Concrete Pore Solutions. *J. Build. Eng.* **2023**, *63*, 105568. [\[CrossRef\]](#)
12. Song, Z.; Liu, L.; Guo, M.-Z.; Cai, H.; Liu, Q.; Donkor, S.; Zhao, H. Inhibition Performance of Extract Reinforcement Corrosion Inhibitor from Waste *Platanus acerifolia* Leaves in Simulated Concrete Pore Solution. *Case Stud. Constr. Mater.* **2024**, *20*, e02992. [\[CrossRef\]](#)
13. Rahmani, M.H.; Dehghani, A.; Salamati, M.; Bahlakeh, G.; Ramezanzadeh, B. Mango Extract Behavior as a Potent Corrosion Inhibitor against Simulated Chloride-Contaminated Concrete Pore Solution: Coupled Experimental and Computer Modeling Studies. *J. Ind. Eng. Chem.* **2024**, *130*, 368–381. [\[CrossRef\]](#)
14. Singh, A.; Ansari, K.R.; AbdelRahim, S.K.; Ali, I.H.; El Ibrahim, B.; Alanazi, A.K.; Younas, M.; Lin, Y. Potential Application of *Ginkgo biloba* Extract as a Green Corrosion Inhibitor for Carbon Steel Reinforcement in Chloride-Polluted Simulated Concrete Pore Solution. *Process Saf. Environ. Prot.* **2024**, *186*, 819–832. [\[CrossRef\]](#)
15. Ghazaee, A.; Pour-Ali, S.; Mahdavi, S.; Tavangar, R.; Khalili, M. Corrosion Inhibition of Steel Rebar in Chloride-Contaminated Concrete Pore Solution: Ecofriendly Glutamic Acid Inhibitor and Its Synergy with Galvanized Coating. *Inorg. Chem. Commun.* **2024**, *167*, 112832. [\[CrossRef\]](#)
16. Ananthkumar, M.; Mini, K.M.; Thilagavathy, P. Eco-Friendly Corrosion Protection of Steel in Simulated Concrete Environments Using *Cassia fistula* Leaf Extract: Electrochemical and Surface Characterization Study. *S. Afr. J. Chem. Eng.* **2025**, *54*, 44–49. [\[CrossRef\]](#)
17. Zhang, Z.; Liu, Y.; Zhu, Y.; Shen, P. Corrosion Inhibition Performance and Mechanism of Glutenin on Reinforcing Steel in Carbonated Concrete Pore Solution: Experimental and Theoretical Studies. *J. Build. Eng.* **2025**, *113*, 114104. [\[CrossRef\]](#)

18. Junaid Ahmed, E.S.; Mohan Ganesh, G. Neem Leaf Extract as a Sustainable Green Inhibitor for Corrosion Inhibition in RCC and Strength Improvement in Concrete, in Conjunction with Spectroscopic Characterization and Statistical Evaluation. *Results Surf. Interfaces* **2026**, *23*, 100771. [\[CrossRef\]](#)
19. Zhang, Z.; Ba, H.; Wu, Z. Sustainable Corrosion Inhibitor for Steel in Simulated Concrete Pore Solution by Maize Gluten Meal Extract: Electrochemical and Adsorption Behavior Studies. *Constr. Build. Mater.* **2019**, *227*, 117080. [\[CrossRef\]](#)
20. Purnima; Tiwari, A.K.; Goyal, S.; Luxami, V. Developing the Inhibition Mechanism for Amide-Based Amino Acids in Carbonated Concrete Environment and Assessing the Migration Ability in Concrete. *J. Build. Eng.* **2023**, *76*, 107048. [\[CrossRef\]](#)
21. Afgan, S.; Kiran, R.; Qi, X.; Bajwa, D.S. Enhancement of Corrosion Resistance and Bond Strength in Rebars Employing Abrasives-Infused Soy-Protein Isolate Coatings. *Constr. Build. Mater.* **2023**, *407*, 133455. [\[CrossRef\]](#)
22. Sajid, H.U.; Kiran, R.; Bajwa, D.S. Soy-Protein and Corn-Derived Polyol Based Coatings for Corrosion Mitigation in Reinforced Concrete. *Constr. Build. Mater.* **2022**, *319*, 126056. [\[CrossRef\]](#)
23. Liao, Q.; Zhuang, E.; Li, J.; Luo, M.; Yu, B.; Hu, J.; Liu, J.; Liu, Q.; Chen, Z.; Chen, B.; et al. Effect of LDHs-ALA on Steel Corrosion in Chloride-Rich Simulated Concrete Pore Solution: Experimental and DFT Studies. *Constr. Build. Mater.* **2024**, *411*, 134756. [\[CrossRef\]](#)
24. Holla, B.R.; Mahesh, R.; Manjunath, H.R.; Anjanapura, V.R. Plant Extracts as Green Corrosion Inhibitors for Different Kinds of Steel: A Review. *Heliyon* **2024**, *10*, e33748. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Sheydaei, M. The Use of Plant Extracts as Green Corrosion Inhibitors: A Review. *Surfaces* **2024**, *7*, 380–403. [\[CrossRef\]](#)
26. Zakeri, A.; Bahmani, E.; Aghdam, A.S.R. Plant Extracts as Sustainable and Green Corrosion Inhibitors for Protection of Ferrous Metals in Corrosive Media: A Mini Review. *Corros. Commun.* **2022**, *5*, 25–38. [\[CrossRef\]](#)
27. Angulo Ramirez, D.E.; Meira, G.R.; Quattrone, M.; John, V.M. A Review on Reinforcement Corrosion Propagation in Carbonated Concrete—Influence of Material and Environmental Characteristics. *Cem. Concr. Compos.* **2023**, *140*, 105085. [\[CrossRef\]](#)
28. Angst, U.; Moro, F.; Geiker, M.; Kessler, S.; Beushausen, H.; Andrade, C.; Lahdensivu, J.; Köliö, A.; Imamoto, K.; von Greve-Dierfeld, S.; et al. Corrosion of Steel in Carbonated Concrete: Mechanisms, Practical Experience, and Research Priorities—A Critical Review by RILEM TC 281-CCC. *RILEM Tech. Lett.* **2020**, *5*, 85–100. [\[CrossRef\]](#)
29. Wang, X.; Liu, J.; Jin, M.; Yan, Y.; Tang, J.; Jin, Z. A Review of Organic Corrosion Inhibitors for Resistance under Chloride Attacks in Reinforced Concrete: Background, Mechanisms and Evaluation Methods. *Constr. Build. Mater.* **2024**, *433*, 136583. [\[CrossRef\]](#)
30. Barbu, C.A.; Fierascu, I.; Semenescu, A.; Cotrut, C.M. Critical Review Regarding the Application of Plant Extracts as Eco-Friendly Corrosion Inhibitors—A Sustainable Interdisciplinary Approach. *Molecules* **2025**, *30*, 3722. [\[CrossRef\]](#) [\[PubMed\]](#)
31. Ayaz, M.; Suleiman, G.S.A.; Altaf, M.; Zafar, A.M.; Cheng, X.; Feng, Y. Polymer and Eco-Friendly Inhibitors for Corrosion Protection of Reinforced Concrete: A Comprehensive Review. *J. Build. Eng.* **2026**, *119*, 115119. [\[CrossRef\]](#)
32. Wang, Q.; Wang, R.; Zhang, Q.; Zhao, C.; Zhou, X.; Zheng, H.; Zhang, R.; Sun, Y.; Yan, Z. Application of Biomass Corrosion Inhibitors in Metal Corrosion Control: A Review. *Molecules* **2023**, *28*, 2832. [\[CrossRef\]](#) [\[PubMed\]](#)
33. ASTM C876-22b; Standard Test Method for Corrosion Potentials of Uncoated Reinforcing Steel in Concrete. ASTM International: West Conshohocken, PA, USA, 2022.
34. Stern, M.; Geary, A.L. Electrochemical Polarization: I. A Theoretical Analysis of the Shape of Polarization Curves. *J. Electrochem. Soc.* **1957**, *104*, 56–63. [\[CrossRef\]](#)
35. Andrade, C.; Alonso, C. Corrosion Rate Monitoring in the Laboratory and On-Site. *Constr. Build. Mater.* **1996**, *10*, 315–328. [\[CrossRef\]](#)
36. ASTM G59-23; Standard Test Method for Conducting Potentiodynamic Polarization Resistance Measurements. ASTM International: West Conshohocken, PA, USA, 2023.
37. ASTM G102-23; Standard Practice for Calculation of Corrosion Rates and Related Information from Electrochemical Measurements. ASTM International: West Conshohocken, PA, USA, 2023.
38. Ribeiro, D.V.; Abrantes, J.C.C. Application of Electrochemical Impedance Spectroscopy (EIS) to Monitor the Corrosion of Reinforced Concrete: A New Approach. *Constr. Build. Mater.* **2016**, *111*, 98–104. [\[CrossRef\]](#)
39. ASTM G109-23; Standard Test Methods for Determining Effects of Chemical Admixtures on Corrosion of Embedded Steel Reinforcement in Concrete Exposed to Chloride Environments. ASTM International: West Conshohocken, PA, USA, 2023.
40. ASTM G180-23; Standard Test Method for Corrosion Inhibiting Admixtures for Steel in Concrete by Polarization Resistance in Cementitious Slurries. ASTM International: West Conshohocken, PA, USA, 2023.
41. Andrade, C.; Alonso, C. Recommendations of RILEM TC 154-EMC: Electrochemical Techniques for Measuring Metallic Corrosion—Test Methods for On-Site Corrosion Rate Measurement of Steel Reinforcement in Concrete by Means of the Polarization Resistance Method. *Mater. Struct.* **2004**, *37*, 623–643. [\[CrossRef\]](#)
42. Vennesland, Ø.; Raupach, M.; Andrade, C. Recommendation of RILEM TC 154-EMC: Electrochemical Techniques for Measuring Corrosion in Concrete—Measurements with Embedded Probes. *Mater. Struct.* **2007**, *40*, 745–758. [\[CrossRef\]](#)
43. Liu, Y.; Song, Z.; Wang, W.; Jiang, L.; Zhang, Y.; Guo, M.; Song, F.; Xu, N. Effect of Ginger Extract as Green Inhibitor on Chloride-Induced Corrosion of Carbon Steel in Simulated Concrete Pore Solutions. *J. Clean. Prod.* **2019**, *214*, 298–307. [\[CrossRef\]](#)

44. Naderi, R.; Bautista, A.; Velasco, F.; Soleimani, M.; Pourfath, M. Use of Licorice Plant Extract for Controlling Corrosion of Steel Rebar in Chloride-Polluted Concrete Pore Solution. *J. Mol. Liq.* **2022**, *346*, 117856. [\[CrossRef\]](#)
45. Harouat, A.; Bezzar, A.-I.; Sail, L. Pomegranate Peel Extract as a Sustainable Corrosion Inhibitor on Steel in a Simulated Concrete Pore Solution and Mortar: Experimental and Theoretical Studies. *Eur. J. Environ. Civ. Eng.* **2024**, *28*, 684–717. [\[CrossRef\]](#)
46. Singh, A.; Ansari, K.R.; Ali, I.H.; Alanazi, A.K.; Lin, Y.; Al-Moubaraki, A.H. Development of Green and Sustainable Corrosion Inhibitor for Steel Rebar in Chloride-Polluted Simulated Concrete Pore Solution Using Seed Extract of *Psoralea corylifolia* (Badranj Boya). *Z. Phys. Chem.* **2023**, *237*, 1849–1862. [\[CrossRef\]](#)
47. Ben Harb, M.; Abubshait, S.; Etteyeb, N.; Kamoun, M.; Dhoub, A. Olive Leaf Extract as a Green Corrosion Inhibitor of Reinforced Concrete Contaminated with Seawater. *Arab. J. Chem.* **2020**, *13*, 4846–4856. [\[CrossRef\]](#)
48. Al-Akhras, N.; Mashaqbeh, Y. Potential Use of Eucalyptus Leaves as Green Corrosion Inhibitor of Steel Reinforcement. *J. Build. Eng.* **2021**, *35*, 101848. [\[CrossRef\]](#)
49. Liu, C.; Liu, Y.; Xia, Z.; Wang, Z.; Wu, B. Coconut Coir Dust Extract as a Novel Green Corrosion Inhibitor for Carbon Steel in the Chloride-Contaminated Concrete Pore Solution. *J. Build. Eng.* **2024**, *82*, 108194. [\[CrossRef\]](#)
50. Purnima; Goyal, S.; Luxami, V. Exploring the Corrosion Inhibition Mechanism of Serine (Ser) and Cysteine (Cys) in Alkaline Concrete Pore Solution Simulating Carbonated Environment. *Constr. Build. Mater.* **2023**, *384*, 131433. [\[CrossRef\]](#)
51. Zhu, Y.; Yang, J.; Zhang, Z.; Shen, P. Ovalbumin as a Green Corrosion Inhibitor for Steel in Chloride-Contaminated Simulated Concrete Pore Solutions: Electrochemical, Morphological, and Theoretical Studies. *J. Mol. Struct.* **2026**, *1349*, 143689. [\[CrossRef\]](#)
52. Bahraq, A.A.; Obot, I.B.; Al-Osta, M.A.; Ibrahim, M.; Ahmad, S.; Malede, Y.C. Electrochemical, Surface, and Molecular-Level Investigation of 2-Mercaptopyrimidine as a Green Corrosion Inhibitor for Steel in Chloride-Contaminated Concrete Pore Solution. *Case Stud. Constr. Mater.* **2026**, *24*, e06185. [\[CrossRef\]](#)
53. Limco, R.A.; Bacosa, H.P.; Lubguban, A.A.; Buluran, J.S. *Morinda citrifolia* (Noni) Leaf Extract as Corrosion Inhibitor for Steel-Reinforced Concrete in Saline Environment. *Int. J. Environ. Sci. Technol.* **2020**, *17*, 4531–4540. [\[CrossRef\]](#)
54. Subbiah, K.; Lee, H.-S.; Mandal, S.; Park, T. Conifer Cone (*Pinus resinosa*) as a Green Corrosion Inhibitor for Steel Rebar in Chloride-Contaminated Synthetic Concrete Pore Solutions. *ACS Appl. Mater. Interfaces* **2021**, *13*, 43676–43695. [\[CrossRef\]](#) [\[PubMed\]](#)
55. Asipita, S.A.; Ismail, M.; Majid, M.Z.A.; Majid, Z.A.; Abdullah, C.; Mirza, J. Green *Bambusa arundinacea* Leaves Extract as a Sustainable Corrosion Inhibitor in Steel Reinforced Concrete. *J. Clean. Prod.* **2014**, *67*, 139–146. [\[CrossRef\]](#)
56. Palanisamy, S.P.; Maheswaran, G.; Selvarani, A.G.; Kamal, C.; Venkatesh, G. *Ricinus communis*—A Green Extract for the Improvement of Anti-Corrosion and Mechanical Properties of Reinforcing Steel in Concrete in Chloride Media. *J. Build. Eng.* **2018**, *19*, 376–383. [\[CrossRef\]](#)
57. Naderi, R.; Bautista, A.; Shagñay, S.; Velasco, F. Licorice (*Glycyrrhiza glabra*) as Corrosion Inhibitor of Carbon Steel Reinforcing Bars in Mortar and Its Synergic Effect with Nitrite. *J. Ind. Eng. Chem.* **2024**, *129*, 620–633. [\[CrossRef\]](#)
58. Naderi, R.; Bautista, A.; Velasco, F.; Soleimani, M.; Pourfath, M. Green Corrosion Inhibition for Carbon Steel Reinforcement in Chloride-Polluted Simulated Concrete Pore Solution Using *Urtica dioica* Extract. *J. Build. Eng.* **2022**, *58*, 105055. [\[CrossRef\]](#)
59. Pradipta, I.; Kong, D.; Tan, J.B.L. Natural Organic Antioxidants from Green Tea Inhibit Corrosion of Steel Reinforcing Bars Embedded in Mortar. *Constr. Build. Mater.* **2019**, *227*, 117058. [\[CrossRef\]](#)
60. Okeniyi, J.O.; Popoola, A.P.I.; Okeniyi, E.T. *Cymbopogon citratus* and NaNO₂ Behaviours in 3.5% NaCl-Immersed Steel-Reinforced Concrete: Implications for Eco-Friendly Corrosion Inhibitor Applications for Steel in Concrete. *Int. J. Corros.* **2018**, *2018*, 5949042. [\[CrossRef\]](#)
61. Okeniyi, J.O.; Loto, C.A.; Popoola, A.P.I. Effects of *Phyllanthus muellerianus* Leaf-Extract on Steel-Reinforcement Corrosion in 3.5% NaCl-Immersed Concrete. *Metals* **2016**, *6*, 255. [\[CrossRef\]](#)
62. Okeniyi, J.O.; Ikotun, J.O.; Akinlabi, E.T.; Okeniyi, E.T. Anticorrosion Behaviour of *Rhizophora mangle* L. Bark-Extract on Concrete Steel-Rebar in Saline/Marine Simulating-Environment. *Sci. World J.* **2019**, *2019*, 6894714. [\[CrossRef\]](#) [\[PubMed\]](#)
63. López-León, L.D.; Juárez-Islas, M.A.; Bassam, A.; Pérez-Callejas, A.D.; Castaneda-Robles, I.E. Electrochemical Behavior of a Cactus Mucilage-Based Corrosion-Resistant Coating. *Int. J. Electrochem. Sci.* **2019**, *14*, 10016–10031. [\[CrossRef\]](#)
64. Hernández, E.F.; Cano-Barrita, P.F.D.J.; León-Martínez, F.M.; Torres-Acosta, A.A. Performance of Cactus Mucilage and Brown Seaweed Extract as a Steel Corrosion Inhibitor in Chloride Contaminated Alkaline Media. *Anti-Corros. Methods Mater.* **2017**, *64*, 529–539. [\[CrossRef\]](#)
65. Venkatesh, G.; Kamal, C.; Vennila, P.; Kaya, S.; Annamalai, M.G.L.; El Ibrahim, B. Sustainable Corrosion Inhibitor for Steel Embedded in Concrete by Guar Gum: Electrochemical and Theoretical Analyses. *Appl. Surf. Sci. Adv.* **2022**, *12*, 100328. [\[CrossRef\]](#)
66. Martínez-Molina, W.; Torres-Acosta, A.; Hernández-Leos, R.; Alonso-Guzman, E.; Mendoza-Pérez, I.; Martínez-Peña, I. The Inhibitive Properties of Nopal Slime on the Corrosion of Steel in Chloride-Contaminated Mortar. *Anti-Corros. Methods Mater.* **2016**, *63*, 65–71. [\[CrossRef\]](#)
67. Zhang, F.; Chen, C.; Hou, R.; Li, J.; Cao, Y.; Dong, S.; Lin, C.; Pan, J. Investigation and Application of Mussel Adhesive Protein Nanocomposite Film-Forming Inhibitor for Reinforced Concrete Engineering. *Corros. Sci.* **2019**, *153*, 333–340. [\[CrossRef\]](#)

68. Zhang, Z.; Yang, B.; Tai, B.; Zhu, Y. Effect of Maize Gluten Meal Extract as Natural Corrosion Inhibitor on Steel in Mortar Corroded by Chloride. *J. Build. Eng.* **2022**, *62*, 105394. [[CrossRef](#)]
69. Shubina, V.; Gaillet, L.; Chaussadent, T.; Meylheuc, T.; Creus, J. Biomolecules as a Sustainable Protection against Corrosion of Reinforced Carbon Steel in Concrete. *J. Clean. Prod.* **2016**, *112*, 666–671. [[CrossRef](#)]
70. Liu, Y.; Shi, J. Corrosion Resistance of Carbon Steel in Alkaline Concrete Pore Solutions Containing Phytate and Chloride Ions. *Corros. Sci.* **2022**, *205*, 110451. [[CrossRef](#)]
71. Argiz, C.; Arroyo, C.; Bravo, A.; Moragues, A.; Andrade, C.; Bolzoni, F. L-Ascorbic Acid as an Efficient Green Corrosion Inhibitor of Steel Rebars in Chloride Contaminated Cement Mortar. *Materials* **2022**, *15*, 8005. [[CrossRef](#)] [[PubMed](#)]
72. Song, Z.; Cai, H.; Liu, Q.; Jiang, L.; Chu, H. Performance of Corrosion Inhibitor Extracted from Enzymatic Hydrolysate of Waste *Platanus acerifolia* Leaves. *J. Ind. Eng. Chem.* **2022**, *111*, 464–479. [[CrossRef](#)]
73. Liu, Q.; Song, Z.; Han, H.; Donkor, S.; Jiang, L.; Wang, W.; Chu, H. A Novel Green Reinforcement Corrosion Inhibitor Extracted from Waste *Platanus acerifolia* Leaves. *Constr. Build. Mater.* **2020**, *260*, 119695. [[CrossRef](#)]
74. ElShami, A.A.; Bonnet, S.; Makhoulouf, M.H.; Khelidj, A.; Leklou, N. Novel Green Plants Extract as Corrosion Inhibiting Coating for Steel Embedded in Concrete. *Pigment Resin Technol.* **2020**, *49*, 501–514. [[CrossRef](#)]
75. Kanwal, M.; Khushnood, R.A.; Shahid, M.; Wattoo, A.G. An Integrated and Eco-Friendly Approach for Corrosion Inhibition and Microstructural Densification of Reinforced Concrete by Immobilizing *Bacillus subtilis* in Pyrolytic Sugarcane-Bagasse. *J. Clean. Prod.* **2022**, *355*, 131785. [[CrossRef](#)]
76. Erşan, Y.Ç.; Van Tittelboom, K.; Boon, N.; De Belie, N. Nitrite Producing Bacteria Inhibit Reinforcement Bar Corrosion in Cementitious Materials. *Sci. Rep.* **2018**, *8*, 14092. [[CrossRef](#)] [[PubMed](#)]
77. Erşan, Y.Ç.; Verbruggen, H.; De Graeve, I.; Verstraete, W.; De Belie, N.; Boon, N. Nitrate Reducing CaCO₃ Precipitating Bacteria Survive in Mortar and Inhibit Steel Corrosion. *Cem. Concr. Res.* **2016**, *83*, 19–30. [[CrossRef](#)]
78. Kanwal, M.; Khushnood, R.A.; Adnan, F.; Wattoo, A.G.; Jalil, A. Assessment of the MICP Potential and Corrosion Inhibition of Steel Bars by Biofilm Forming Bacteria in Corrosive Environment. *Cem. Concr. Compos.* **2023**, *137*, 104937. [[CrossRef](#)]
79. ISO 14040:2006; Environmental Management—Life Cycle Assessment—Principles and Framework. International Organization for Standardization (ISO): Geneva, Switzerland, 2006.
80. ISO 14044:2006; Environmental Management—Life Cycle Assessment—Requirements and Guidelines. International Organization for Standardization (ISO): Geneva, Switzerland, 2006.
81. Organisation for Economic Co-operation and Development. Test No. 301: Ready Biodegradability. In *OECD Guidelines for the Testing of Chemicals, Section 3*; OECD Publishing: Paris, France, 1992. [[CrossRef](#)]
82. ASTM C1556-22; Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion. ASTM International: West Conshohocken, PA, USA, 2022.
83. ISO 16204:2012; Durability—Service Life Design of Concrete Structures. International Organization for Standardization (ISO): Geneva, Switzerland, 2012.
84. ISO 16311-2:2024; Maintenance and Repair of Concrete Structures—Part 2: Assessment of Existing Concrete Structures. International Organization for Standardization (ISO): Geneva, Switzerland, 2024.

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