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Green Corrosion Inhibitors and Anticorrosive Coatings from Inhibition Mechanisms to Sustainable Coating Design

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ABSTRACT

Developing corrosion protection with lower environmental burdens requires both effective interfacial chemistry and durable coating architecture. This narrative review examined key studies on plant extracts, polyphenols, amino acids, biomass-derived ionic liquids, biopolymers, and renewable resin components, with an emphasis on their integration into anticorrosive coatings. We assessed published evidence by substrate, electrolyte, concentration, film thickness, exposure duration, and measurement method. Adsorption, metal-ion complexation, barrier formation, and controlled inhibitor release explained complementary protection routes. However, inhibition efficiencies measured in acidic solutions did not establish coating durability in chloride environments. Tannic acid exemplified this context dependence: it could inhibit corrosion, accelerate attack at insufficient concentration, or form a surface layer that required additional barrier protection. Encapsulation improved inhibitor delivery, whereas lignin and vegetable-oil resins offered routes to replace conventional binder components. The strongest coating evidence combined prolonged exposure with impedance, adhesion or defect assessment. Biomass origin and waterborne processing alone did not establish low toxicity or a favourable life cycle. Progress therefore depended on reproducible feedstocks, compatible formulations, release and leachate measurements, and validation under relevant service conditions. Green corrosion protection emerged as a property of the complete material system and its service history, rather than an intrinsic label attached to a natural ingredient.

Keywords: Green corrosion inhibitor; anticorrosive coating; tannic acid; chitosan; lignin; controlled release; sustainable materials.

INTRODUCTION

Corrosion control increasingly draws on renewable molecules that can interact with metal surfaces and on coatings that reduce exposure to aggressive species. Aqueous plant extracts have inhibited steel dissolution in acidic media, while extract-based systems have also been examined in synthetic seawater. [1,2] These applications address different operating conditions: an inhibitor continuously available in a process liquid has a different delivery requirement from an additive immobilized in a cured film. A useful review must connect these two scales. Molecular adsorption can slow an interfacial reaction, but coating protection also depends on transport, adhesion, dispersion and resistance to damage. Tannic-acid-loaded

silica in epoxy and epoxidized lignin in resins illustrate how inhibitor chemistry and formulation control interact. [3,4] This review evaluates the supporting evidence and distinguishes renewable sourcing from demonstrated environmental benefit. It focuses on steel in acidic and chloride-containing environments; conclusions do not automatically transfer to other metals.

REVIEW APPROACH

We completed a focused narrative search of primary journal papers available through publisher websites on 20 October 2026. Searches combined green corrosion inhibitor, plant extract, tannic acid, chitosan, lignin, anticorrosive coating, waterborne epoxy and controlled release. We selected recent original studies with explicit formulation or inhibitor identity, a defined metal and electrolyte, and interpretable experimental endpoints. Official test-method descriptions informed assessment of measurement quality. We synthesized evidence qualitatively; the search was not an exhaustive systematic review, and we did not pool heterogeneous efficiency values. Figure selection additionally required verified reuse permission and an original source caption.

CHEMICAL BASIS OF GREEN INHIBITION

In aqueous corrosion, anodic metal dissolution is coupled to a cathodic reaction. Inhibitors can alter either process or both by occupying reactive sites, changing the local double layer, or producing a less permeable interfacial film. Oxygen- and nitrogen-containing functionalities are common in the compounds considered here. Their behaviour depends on protonation, solubility, competitive adsorption, metal-ion availability and the evolving oxide or corrosion-product surface. Chemically defined salts and amino acids help isolate these effects from the compositional complexity of crude extracts. [5,6]. Polyphenols provide multiple hydroxyl groups for surface interaction and metal-ion complexation. Nevertheless, complex formation can favour either a protective deposit or soluble species that sustain dissolution. Jia et al. demonstrated this distinction for tannic acid on W18Cr4V tool steel in 10 wt% acetic acid: low tannic-acid concentrations promoted attack, whereas higher concentrations produced net inhibition.[7] Consequently, optimize inhibitor concentration for the intended substrate and medium; a threshold established in one experiment is not a general design rule.

Adsorption isotherms and molecular calculations are useful supporting tools, but their evidential roles should be limited. A good fit to a Langmuir relation does not establish a single adsorbate, uniform sites or a unique bonding mechanism in a multicomponent extract. Likewise, calculated molecular orbital energies support reactivity hypotheses rather than validating a corrosion lifetime. Electrochemistry, surface chemistry and microscopy should test the same proposed mechanism, including whether the protecting species remains attached after rinsing or exposure. [1,8]

INHIBITOR FAMILIES AND CONDITION DEPENDENCE

Plant extracts and biomass valorization

Extracts offer accessible mixtures of potential adsorbates, but solvent choice and feedstock processing influence the material actually tested. Sun et al. used an aqueous extract of *Ambrosia trifida* leaves, whereas Royani et al. obtained *Aloe vera* extract by methanol-water maceration. [1,2] These are distinct process routes despite a shared plant origin. For reproducibility, inhibitor concentration should be accompanied by botanical identity, sampled tissue, drying conditions, extraction yield, and a compositional fingerprint. Reporting only the mass of crude extract leaves the active fraction unresolved. Synergistic formulations can improve performance but add another variable to optimization. In 15% HCl, *Canarium strictum* extract with a small KI addition outperformed either constituent at the selected conditions; performance

declined as temperature increased.[9] Such results support testing mixtures with extract-only, salt-only and combined controls. They do not establish that a synergist will remain beneficial after incorporation into a polymer, where release and partitioning differ.

Defined molecules and modified biopolymers

L-histidine, choline syringate and L-arginine-grafted chitosan represent increasingly different combinations of molecular identity and polymer functionality. [5,6,8] A defined amino acid can be compared on a molar basis, while a grafted polysaccharide also requires molecular-weight and substitution information. The advantages of traceability and chemical design should therefore be balanced against extra synthesis, purification and characterization requirements. Table 1 retains the test conditions needed to interpret representative results.

Table 1. Representative inhibitor results with their original experimental context

Inhibitor and source	Metal and exposure conditions	Reported endpoint
Ambrosia trifida water extract[1]	Q235; 1 M HCl; 1000 mg L^{-1}; 298 K; 24 h	95.9% by mass loss; 99.0% by EIS at 24 h.
Aloe vera extract[2]	API 5L; synthetic seawater; 300 mg L^{-1}; 310 K; 10 min OCP stabilization	83.75% PDP; 88.60% EIS.
Canarium extract with KI[9]	Mild steel; 15% HCl; 700 ppm extract + 5 ppm KI; 293 K; 6 h	96.8% by mass loss; extract alone 92.2%.
L-histidine[6]	AISI 1018; 3.5 wt% NaCl; 1000 ppm; 25 °C	About 88% mass-loss inhibition at 168 h; EIS 72% after 1 h OCP.
Choline syringate[5]	AS1020; 0.01 M NaCl; 10 mM; 24 h	Reported polarization inhibition 96%.
L-arginine-grafted chitosan[8]	Mild steel; 0.5 M HCl; 500 ppm; 303 K; 1 h OCP	91.43% by EIS.
Tannic acid[7]	W18Cr4V; 10 wt% acetic acid; 20 h	Mass-loss inhibition −11.25% at 1 wt% TA and 64.11% at 10 wt% TA.

EIS denotes electrochemical impedance spectroscopy; PDP, potentiodynamic polarization; OCP, open-circuit potential. A negative efficiency denotes faster corrosion than the corresponding blank. Each percentage is a within-study comparison, not a ranking across materials.

FROM SURFACE FILMS TO DURABLE COATINGS

Polyphenol layers and protective overcoats

An adherent surface layer is a useful starting point, but adhesion during deposition does not guarantee resistance to water and ions. Sesia et al. examined natural chestnut and quebracho tannin layers and showed the importance of pretreatment, dissolution medium and deposition conditions. The selected chestnut-tannin specimen in Figure 1 developed corrosion products and partially detached after 24 h in 3.5 wt% NaCl.[10] This observation supports using such chemistry only after the required barrier function is established.

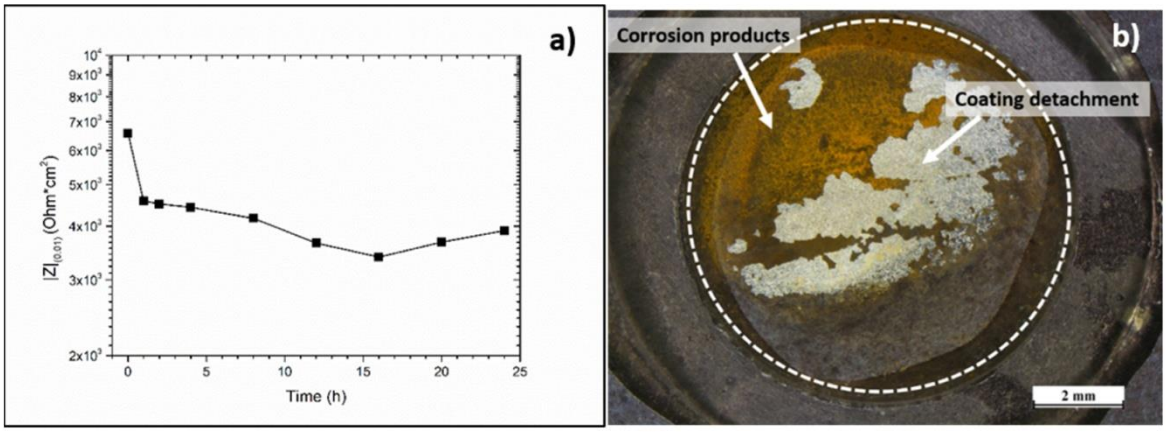


Figure 1. Response of a chestnut-tannin layer on carbon steel during 24 h in 3.5 wt% NaCl: (a) low-frequency impedance and (b) the exposed surface. Reproduced from Sesia et al., original Figure 6.[10] © The Authors 2024, CC BY 4.0, creativecommons.org/licenses/by/4.0/. Unchanged; resized.

Layered design can address that limitation. Lopez de Lacalle et al. polymerized phenolic deep eutectic mixtures on steel, generating a metal-polyphenol interfacial layer, and added a hydrophobic polyacrylate topcoat. This bilayer system achieved very high polarization efficiencies after 24 h in dilute chloride solution.[11] The overcoat is integral to the result: the water-soluble functional primer should not be credited with the complete system performance. This distinction is central when translating a promising molecule into a coating specification.

Biopolymer containers and inhibitor delivery

Encapsulation addresses a practical conflict: the active molecule must be retained during storage and undamaged during service, yet become available when protection is needed. Chitosan and alginate can assemble through polyelectrolyte interactions and carry an inhibitor within a composite deposit. Kamburova et al. incorporated caffeine-loaded containers into zinc on steel and followed polarization resistance for 40 days. Separate release measurements showed greater caffeine release at lower pH.[12] Release from a particle suspension, however, does not quantify the flux reaching a defect inside a coating. A subsequent study combined ZnO and caffeine within chitosan-alginate nanocontainers before electrodeposition, as shown in Figure 2.[13] The formulation combines a zinc matrix, an inorganic component and an organic inhibitor, so its protection can involve sacrificial dissolution, barrier effects and interfacial inhibition. Controls should identify each component's contribution. For application, particle stability in the deposition bath and consistent deposited loading are as important as encapsulation efficiency.

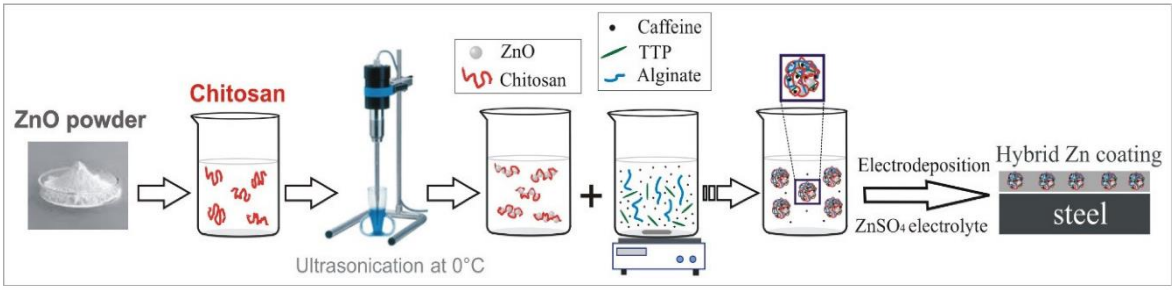


Figure 2. Preparation of ZnO and caffeine-containing chitosan-alginate nanocontainers and their incorporation into zinc coatings. Reproduced from Kamburova et al., original Scheme 1.[13] © The Authors 2025, CC BY 4.0, creativecommons.org/licenses/by/4.0/. Original labels retained; resized.

Responsive fillers and defect protection

Mesoporous silica provides a reservoir that can separate inhibitor storage from the surrounding resin. Wang et al. reported strong barrier retention for epoxy containing 5 wt% tannic-acid-loaded silica; excess filler impaired performance through agglomeration. Their proposed functions are reproduced in Figure 3.[3] Corrosion indication and interfacial protection arise from related chemistry, but a visible colour change is not a quantitative measure of remaining coating life.

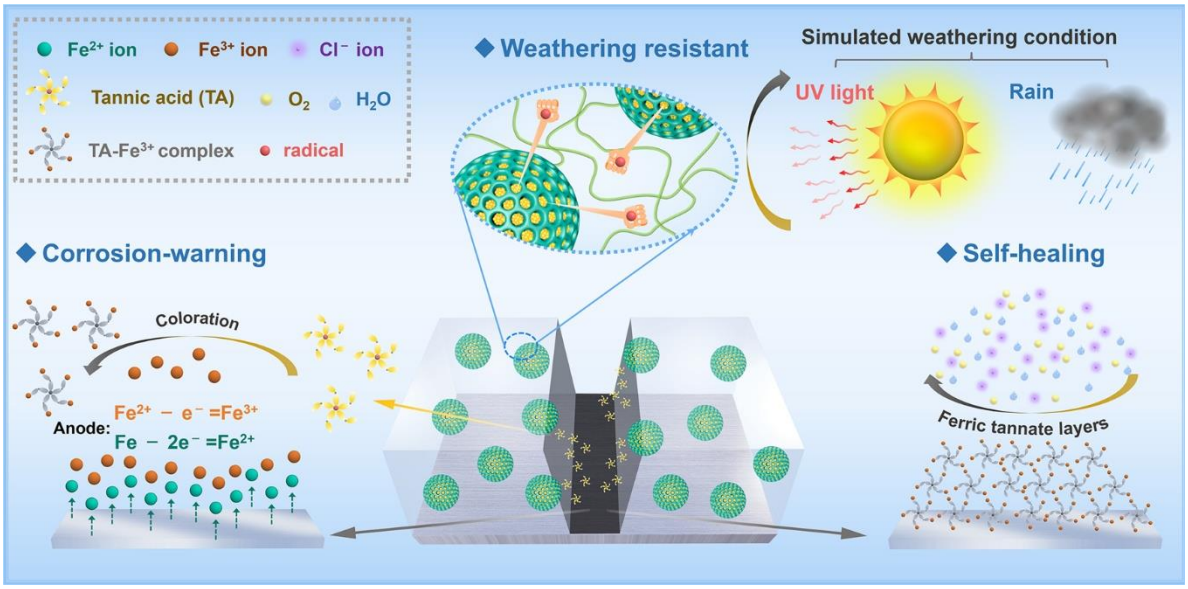


Figure 3. Proposed weathering resistance, corrosion indication and inhibitor-assisted protection in epoxy containing tannic-acid-loaded mesoporous silica. Reproduced from Wang et al., original Figure 9.[3] © The Author(s) 2023, CC BY 4.0, creativecommons.org/licenses/by/4.0/. Unchanged; resized. The depicted self-healing refers to protection at a defect, not physical scratch closure as demonstrated.

Carrier chemistry can also participate directly in protection. Raj et al. introduced tannic-acid-loaded hydroxyapatite into polyolefin; acidic conditions promoted carrier dissolution and release of tannic acid and phosphate species.[14] This design couples delivery to local chemistry, but the finite reservoir remains a limitation. Before claiming autonomous recovery throughout service, test repeated damage, long undamaged immersion, and inhibitor depletion. Plate-like fillers offer another route by increasing the diffusion path through the film. Liu et al. combined graphene oxide with dopamine and tannic acid to improve compatibility with epoxy and preserve high impedance during prolonged chloride immersion.[15] Dispersion is decisive: an additive that introduces aggregates, voids or connected defects can undermine protection despite favourable molecular interactions. Therefore, optimize loading, particle treatment, and cure response together.

Renewable binders and lignin-containing resins

Replacing part of the binder changes the formulation more substantially than adding a small amount of plant-derived inhibitor. Truncali et al. substituted epoxidized Kraft lignin for conventional resin and demonstrated that size fractionation and resin chemistry controlled the outcome. Figure 4 compares the coatings after 1680 h salt spray exposure.[4] The favourable epoxy-novolac formulation did not establish equivalent improvement for the bisphenol-F system. Such differences argue for testing the complete cured network rather than evaluating renewable content in isolation.

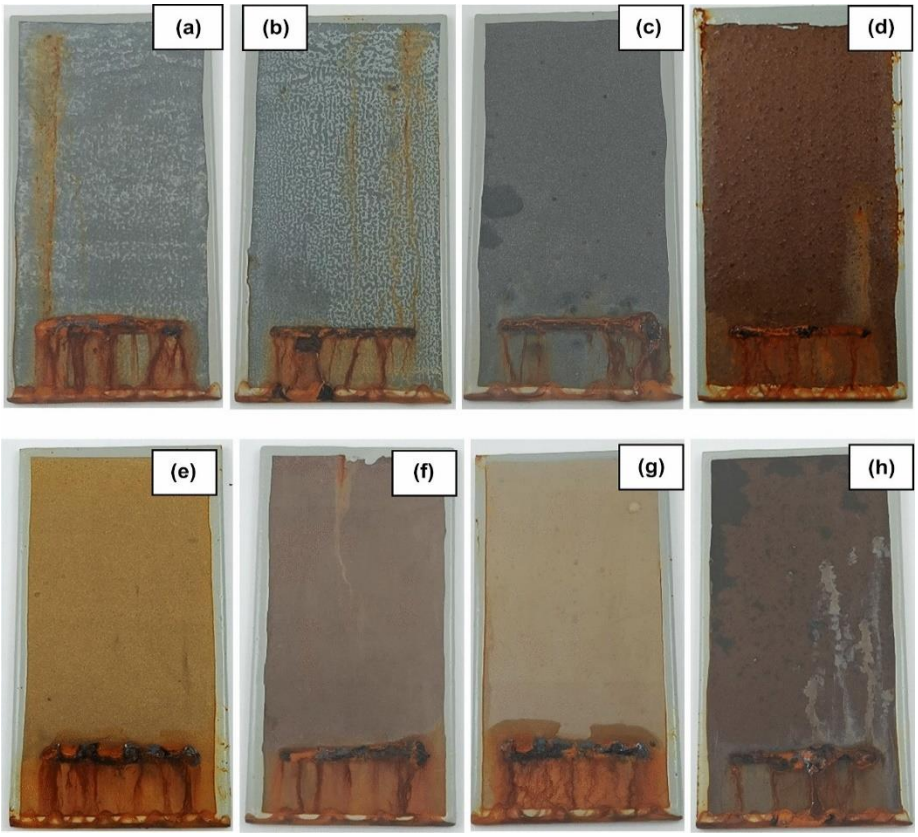


Figure 4. Coated steel after 1680 h salt spray exposure. (a,b) Epoxy-novolac controls; (c) bisphenol-F epoxy control; (d) 25% nonfractionated epoxidized lignin in novolac; (e,f) 25% size-fractionated lignin in novolac; (g) 50% in novolac; (h) 25% in bisphenol-F epoxy. Percentages refer to resin mass. Reproduced from Truncali et al., original Figure 8.[4] © The Author(s) 2024, CC BY 4.0, creativecommons.org/licenses/by/4.0/. Unchanged; resized.

Teijido et al. extended renewable substitution to both an epoxidized soybean-oil resin and a tannic-acid curing component. The resulting films retained protective behaviour during six months of chloride immersion.[16] This is a meaningful duration for laboratory screening, while thermal cure, abrasion, and outdoor exposure remain part of qualification. Table 2 summarizes representative coating evidence using the reported endpoints rather than converting all results into a common percentage.

Table 2 Representative coating systems and the limits of comparison

Coating system	Exposure and film information	Reported result and interpretation
Epoxy with 5 wt% tannic-acid-loaded silica [3]	3.5 wt% NaCl; 28 d; intact coating	|Z| at 0.01 Hz: 4.0×10^8 Ω cm². Higher filler loading was not always beneficial.
Tannic-acid-loaded hydroxyapatite in polyolefin [14]	0.05 M NaCl; 30 d; 18 ± 0.5 µm modified versus 20 ± 0.5 µm blank	Modified coating impedance remained above 10^7 Ω cm². Thickness difference and carrier chemistry matter.
Phenolic polymer primer plus polyacrylate [11]	0.01 M NaCl; 24 h; about 100 µm total film	TA/PCA systems: 99.84%/99.54% polarization inhibition. The topcoat is part of the tested system.
Epoxy novolac with 25 wt% fractionated epoxidized lignin [4]	5 wt% NaCl salt spray; 1680 h; 300 ± 10 µm	2.20 mm rust creep for the best formulation. Results depended on resin and cure stoichiometry.
Soybean-oil epoxy cured with tannic acid [16]	3.5 wt% NaCl; six months; 100 ± 20 µm	Sustained barrier behaviour in immersion. No direct conversion to outdoor service years.

TA, tannic acid; PCA, protocatechuic acid; |Z|, impedance modulus. Impedance, polarization inhibition and rust creep describe different observables. Studies differ in thickness, electrolyte, duration, and damage state.

PERFORMANCE ASSESSMENT AND EVIDENCE QUALITY

Interpreting electrochemical and gravimetric endpoints

Inhibition efficiency is a normalized change from an appropriate blank, rather than an intrinsic property of a compound. For matched current-density and charge-transfer-resistance measurements, commonly used expressions are:

$$\eta_i\,(\%) = 100 \times \left(1 - \frac{i_{corr,inh}}{i_{corr,b}}\right) \quad (1)$$

$$\eta_R\,(\%) = 100 \times \left(1 - \frac{R_{ct,b}}{R_{ct,inh}}\right) \quad (2)$$

Here, i_{corr} is corrosion current density, R_{ct} is fitted charge-transfer resistance, and b and inh denote blank and inhibited specimens. Both efficiencies are expressed as percentages. The resistance expression assumes comparable charge-transfer behaviour; it does not apply to arbitrary coating resistance or impedance modulus. Changes in Tafel slopes or reaction mechanism can invalidate the comparison. A mass-loss efficiency similarly compares rates over the same exposure period. The different efficiencies reported for L-histidine illustrate why method and exposure duration must remain explicit.[6]. For coatings, low-frequency impedance is informative only when the frequency, exposed area, electrolyte and film condition are stated. A fitted coating resistance, charge-transfer resistance and impedance modulus are not interchangeable. ISO 16773-2 addresses acquisition and validation of impedance data, including high-impedance specimens; it does not prescribe interpretation of a particular fitted circuit.[17] A credible report should include the spectra, model justification, fit quality and independent replicates, together with thickness and immersion history.

Testing damage and durability

Defect inhibition, physical crack closure and restoration of an intact barrier are separate outcomes. A dark iron-tannate deposit at a scratch can support interfacial inhibition without restoring the original polymer geometry. Conversely, apparent crack closure needs evidence that transport resistance and adhesion have recovered. Intact, deliberately damaged, empty-carrier and free-inhibitor controls can distinguish these effects.[3,14]. Salt spray enables controlled comparison, but you cannot convert exposure hours directly into service years. ASTM B117 cautions against predicting natural-environment performance from stand-alone salt-spray results and emphasizes replication.[18] Qualification should combine service-relevant cyclic exposure with adhesion, underfilm corrosion and weathering tests. Document coupon preparation, edge sealing and defect geometry to distinguish formulation effects from specimen variability.

ENVIRONMENTAL CREDIBILITY AND SCALE UP

The term green should be supported at the level of the complete formulation and process. Renewable feedstock content, hazardous reagents, solvent recovery, energy demand, leaching and useful coating life are distinct considerations. A low-loading renewable additive may improve performance while leaving most of the binder fossil-derived. Conversely, extensive renewable substitution can be valuable even where further process improvements are needed. Claims should specify which of these changes has actually been demonstrated. Lignin epoxidation illustrates this boundary: the reported route uses epichlorohydrin and organic solvents, and the coating formulation contains xylene.[4] Likewise, Zhu et al. combined waste-leaf carbon, carboxymethyl chitosan and 8-hydroxyquinoline in waterborne epoxy. Their reported protection is promising, but carbonization at 700 °C, chemical activation and the active inhibitor remain part of the process and hazard inventory.[19] Waterborne processing identifies the principal carrier medium; it does not by itself establish negligible emissions or low aquatic impact. Environmental testing should address

leachate from an aged coating, including soluble degradation products and released particles. The amount released per unit protected area and over time is more informative than a label attached to the starting biomass. Biodegradation may be desirable after disposal while rapid degradation during use can shorten protection and increase recoating. Assessment should therefore compare equivalent functions, for example the materials and energy required to protect a defined steel area over a specified maintenance interval. Scale-up also depends on batch consistency. Extract-based products require practical specifications for yield and composition; modified polymers need control of substitution and molecular weight; filled coatings need stable dispersion and reproducible curing. Measure shelf stability, application viscosity, pot life, and adhesion after immersion alongside corrosion endpoints. These are proposed development criteria, not properties established for every material summarized here.

RESEARCH PRIORITIES

The next stage should link molecular screening with formulation-level validation. Promising molecules should be evaluated in the actual matrix, followed through release and depletion, and tested after controlled damage and ageing. Comparative work should report negative outcomes and unsuccessful loadings, which are essential for learning why a formulation fails. Multicriteria selection should consider corrosion performance, adhesion, toxicity, renewable content, application constraints and maintenance requirements together. Data-guided optimization offers a practical route when experimental space is large. Samanta et al. used 492 historical salt-spray results spanning 148 ingredients to propose two new formulations that were then experimentally tested.[20] The dataset was biased toward more effective formulations, which limits generalization. For green coatings, the useful extension is to include environmental and processing descriptors, preserve uncertainty, and validate recommendations on independent formulations rather than treating a predictive model as evidence of sustainability.

CONCLUSION

Green corrosion inhibitors and anticorrosive coatings are most convincing when molecular function, material architecture and exposure conditions are evaluated together. Plant extracts and defined bio-derived molecules provide adsorption and complexation chemistry, while biopolymer containers and responsive fillers regulate delivery. Renewable resins can reduce conventional binder content, provided dispersion, cure and adhesion remain suitable. Across the evidence reviewed, promising results coexist with concentration-dependent acceleration, film detachment, agglomeration and finite inhibitor reservoirs. The appropriate development objective is therefore durable protection with a demonstrated reduction in environmental burden. Reproducible composition, matched controls, transparent electrochemical interpretation and realistic ageing tests are needed to establish that outcome.

Declaration by Authors

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