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Natural Inhibitors for Corrosion Protection of 6061 Aluminum Alloy: A Review

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Abstract

6061 aluminum alloys are widely used in automotive, marine, and aerospace industries, yet their high susceptibility to corrosion in acidic and chloride environments remains a challenge. Bio-based inhibitors from natural sources have emerged as sustainable alternatives to toxic synthetic chemicals. This review synthesizes findings from published studies on AA6061 alloys and composites, integrating evidence from Potentiodynamic Polarization (PDP), Electrochemical Impedance Spectroscopy (EIS), and Scanning Electron Microscopy (SEM). Cross-study evaluations show that inhibition efficiency depends on inhibitor type and mechanism. Reports indicate that *Boswellia serrata* provides only moderate protection (~70%) due to weak physiosorbed films that are unstable under flow, whereas *Alocasia odora* achieves higher efficiency (~94% in HCl) through chemisorption with cathodic inhibition. *Aerva lanata* demonstrates ~88% efficiency in chloride-based fiber-metal laminates via polyphenolic adsorption, while glutathione provides ~80% protection at 0.75 mM through multisite coordination. Pectin consistently achieves the highest efficiency (~95% in mild acidic media) by forming compact polymeric films that increase charge-transfer resistance and reduce double-layer capacitance. This synthesis indicates that chemisorption-based inhibitors (e.g., pectin, Alocasia) generally outperform physisorption-based systems (e.g., Boswellia) because they form stronger and more stable films. Reported studies highlight both advantages and limitations: natural inhibitors are effective and eco-friendly, but most evaluations remain short-term and laboratory-based. Key gaps include durability testing, advanced characterization (XPS, ToF-SIMS, Raman, AFM), galvanic effects in composites, and poor hydrodynamic stability of physisorption systems. Future work should explore hybrid strategies, synergistic multi-inhibitor approaches, and validation under real-sea conditions to enable scalable and industrially viable corrosion protection.

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1. Introduction

Aluminum alloys, particularly 6061, are widely recognized for their unique balance of lightweight nature, high strength-to-weight ratio, ease of fabrication, and inherent corrosion resistance. These properties make them indispensable in industries that require structural efficiency and durability. In the marine sector, aluminum 6061 is extensively applied in ships, naval vessels, and offshore platforms, where its low density reduces structural mass and enhances fuel efficiency. Beyond the maritime industry, it is equally significant in automotive, aerospace, and civil engineering, supporting the development of lightweight vehicles, aircraft, and modern architectural systems [1-7].

Despite these advantages, aluminum alloys remain susceptible to corrosion, particularly in chloride-rich marine environments. Corrosion is a global issue that accounts for about 3.4 percent of GDP losses, although effective prevention strategies can reduce this by 15 to 35 percent [8-10]. For aluminum 6061, the naturally formed oxide film (Al_2O_3) is insufficient in seawater, leading to localized pitting, accelerated degradation, and reduced structural integrity [11-14]. These weaknesses translate into significant economic and safety challenges across marine, automotive, and aerospace industries.

Conventional methods to mitigate corrosion include immersion, spraying, electrodeposition, and metallic or ceramic coatings [15,16]. Organic coatings have also been employed as

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supplementary barriers, yet their long stabilization periods and poor durability under seawater limit their effectiveness [17-20]. Corrosion inhibitors present a more practical solution. Traditional inhibitors such as nitrites and chromates reduce corrosion by adsorbing onto the metal–solution interface, but their toxicity and ecological risks have led to bans in several regions [21-26]. In contrast, green inhibitors derived from plant extracts, biopolymers, and biomass wastes offer biodegradability, renewability, and environmental compatibility [27,28]. Their effectiveness is closely tied to their adsorption behavior on aluminum surfaces, involving both physisorption and chemisorption, which improve charge transfer resistance and stabilize the passive layer [29,30].

The performance of inhibitors is strongly influenced by environmental conditions such as salinity, temperature, dissolved oxygen, pH, and biofouling [31-33]. Dynamic factors like flow rate and immersion time also affect inhibitor film stability [34,35]. Recent studies indicate that combining green inhibitors with advanced coatings can produce synergistic protective systems, extending the service life of aluminum 6061 in aggressive environments [36-37]. However, most studies remain limited to short-term laboratory conditions in simplified electrolytes such as NaCl or HCl. Advanced characterization and molecular simulations are rarely applied, and inhibition efficiency often declines under high temperature and flow conditions. Strategies such as dual inhibitors, hybrid systems, or electrophoretic deposition are underexplored, highlighting the need for more comprehensive and scalable approaches for sustainable corrosion protection.

2. Corrosion Analysis Methods

A number of studies have applied integrated electrochemical and surface characterization techniques to evaluate the corrosion behavior of aluminum alloys and the performance of protective solutions. Electrochemical Impedance Spectroscopy (EIS) has been widely reported as an essential tool for analyzing corrosion resistance. By providing information on charge transfer resistance, double-layer capacitance, and passive film stability, EIS enables a detailed understanding of inhibitor effectiveness in reducing the electrochemical interaction between the alloy and the corrosive environment [38].

Complementing EIS, Potentiodynamic Polarization (PDP) has been frequently employed to determine corrosion rate, corrosion potential, and to classify the type of inhibition mechanism (anodic, cathodic, or mixed). Several investigations have highlighted that PDP results provide a quantitative measure of corrosion resistance under aggressive environmental conditions, thereby offering a clearer view of the dominant mode of corrosive attack [39].

In addition to electrochemical methods, Scanning Electron Microscopy (SEM) has been extensively utilized to validate electrochemical findings through direct surface observation. SEM images reported in prior works consistently reveal changes in surface morphology, such as cracks, pits, and deposition of corrosion products, thus confirming the formation of protective films or the extent of degradation in the absence of inhibitors [40].

Overall, the literature demonstrates that the combination of EIS, PDP, and SEM provides a comprehensive framework for understanding both the electrochemical and morphological aspects of corrosion in aluminum alloys. This integrated approach has been repeatedly emphasized in review studies as a reliable strategy for evaluating inhibitor performance and guiding the development of sustainable corrosion protection systems for 6061 aluminum alloy.

2.1. Evaluation of Electrochemical Impedance Spectroscopy (EIS)

Electrochemical Impedance Spectroscopy (EIS) is a technique for measuring the impedance response of electrodes to AC signals at various frequencies. EIS is used to determine electrode properties, such as resistance, capacitance, and reactance, as well as to analyze corrosion processes and protective coating behavior in 6061 aluminum alloy [41,42].

As shown in Table 1, Based on cross-study evaluations, the application of Electrochemical Impedance Spectroscopy (EIS) to AA6061 aluminum alloy and its variants (Al–SiC composites and fiber–metal laminates) confirms that an increase in charge-transfer resistance (Rct/Rp) and a decrease in electrical double-layer capacitance (Cdl) are the primary indicators of successful inhibition by natural compounds through protective film formation. In mild acidic media (0.025 M HCl), pectin exhibited the most promising performance, with a significant rise in Rp, a marked reduction in Cdl, and inhibition efficiency up to approximately 95%. The adsorption mechanism followed a Langmuir chemisorption model, corroborated by SEM–EDX evidence, resulting in a compact and thermally stable protective layer. *Alocasia odora* achieved approximately 94% efficiency in 0.5 M HCl through a predominantly cathodic inhibition mechanism, as reflected by an increase in Rp and improved surface morphology. Glutathione was also effective on 6061Al–SiC, producing increased Rp and reduced Cdl via adsorption of nitrogen-, oxygen-, and sulfur-containing donor groups, although its efficiency remained below that of pectin and *Alocasia*. Under neutral chloride conditions (3.5% NaCl), *Aerva lanata* improved Rct and achieved inhibition efficiency of approximately 88% in AA6061-FML at optimum concentration, although the film was sensitive to variations in concentration and test conditions. Meanwhile, *Boswellia serrata* enhanced impedance at low flow conditions and moderate temperature; however, EIS thermodynamic parameters indicated predominantly physical adsorption, rendering the film less stable under aggressive conditions. Mechanistically, the differences in inhibitor performance are primarily dictated by the density of electron-donor sites, the ability of molecules to form compact protective films, and stability against hydrodynamic and thermal perturbations. Accordingly, pectin and *Alocasia odora* emerge as the most promising candidates, while glutathione, *Aerva lanata* and *Boswellia serrata* remain relevant for specific environmental applications.

The novelty of this review lies in systematically mapping natural inhibitors across different corrosive environments (mild acids, strong acids and chloride media) and substrate variations (alloys, composites, laminates), thus providing a comprehensive framework for understanding how molecular physicochemical properties determine protective performance as evidenced by EIS parameters. This synthesis not only consolidates individual findings but also identifies a universal pattern, namely that inhibition effectiveness is governed by the interplay between electron-donor adsorption and morphological film stability.

Future research should focus on three directions, such as standardization of EIS protocols to enable valid cross-laboratory comparison, long-term evaluation under dynamic service conditions (flow, wet–dry cycles, abrasion and biofouling) to assess industrial-scale durability; and integration of green inhibitors with hybrid coating technologies (e.g., organic–nanocomposite systems) to enhance film stability in marine and chemical environments.

Practical implications of this review suggest that pectin is highly suitable for environmentally friendly acid cleaning or pickling in mild acidic conditions; *Alocasia odora* is a strong candidate for processes in strong acidic media relevant to automotive and aerospace industries; glutathione offers sustainable and biocompatible options; *Aerva lanata* holds promise for protecting fiber–metal laminates in marine applications; and *Boswellia serrata* may be beneficial under low-flow or localized

Table 1. Reported EIS results for AA6061 aluminum alloy

No.	Reference	Optimized parameters	Main result
1	[43]	Total impedance, Nyquist curve shape, equivalent circuit model, effect of flow rate on impedance	EIS revealed that corrosion protection by Boswellia serrata was effective in forming a protective film, especially at low flow rates and low temperatures. Nyquist curves and circuit models showed that the protective film was imperfect but still inhibited the charge transfer process.
2	[44]	Rct (charge transfer resistance), Rp (polarization resistance), Inhibition efficiency (η%), RL (inductive resistance), Ru (solution resistance)	EIS showed that Alocasia odora extract significantly improved the corrosion resistance and inhibition efficiency of aluminum in HCl through the formation of an effective protective layer.
3	[45]	Diameter Nyquist plot, charge transfer resistance, CPE (Constant Phase Element), phase bode plot	EIS showed a significant increase in charge transfer resistance at 1000 ppm Boswellia serrata concentration, 303 K temperature, and 4 L/min flow rate, indicating high effectiveness of the inhibitor in forming a protective film against erosion-corrosion.
4	[46]	Charge transfer resistance, constant phase element, coefficient n, inhibition efficiency (%η, of Rct) were calculated using Nyquist curve diameter	EIS showed that *Aerva lanata* extract effectively inhibited the corrosion of 6061 aluminum-based FML in 3.5% NaCl medium.
5	[47]	Resistance to charge transfer, polarization resistance, Constant Phase Element (CPE)/double-layer capacitance, inhibition efficiency	EIS showed that the addition of glutathione significantly increased the polarization resistance (R_p) and decreased the double-layer capacitance.
6	[48]	Polarization resistance (Rp or total Rp), Double Layer Capacitance (Cdl), Constant Phase Element (CPE, Q and coefficient a), Charge Transfer Resistance (Rct), Nyquist Plot Diameter (Semi-circle), Equivalent Circuit Model	EIS showed that the addition of pectin significantly increased the polarization resistance (Rp), decreased the double layer capacitance (Cdl), and formed a protective layer through chemisorption.

exposure systems. Overall, this literature review provides not only a synthesis of experimental evidence but also a conceptual framework to guide the selection and development of more effective and application-specific green inhibitors for next-generation aluminum alloys.

2.1.1 Electrochemical Impedance Spectroscopy (EIS) insights from literature on AA6061 and natural inhibitors

The following results are synthesized from prior studies and presented as a comparative review. The Nyquist plots in Fig. 1 show how hydrodynamic conditions, inhibitor concentration, and surface characteristics influence the corrosion protection of AA6061 and its composites. Larger semicircle diameters indicate higher charge-transfer resistance (Rct/Rp) and lower corrosion rates. Collectively, the reviewed studies reveal that equivalent circuit fitting with a constant phase element (CPE) links reduced double-layer capacitance (Cdl) to compact protective films, while a higher n-exponent reflects improved surface homogeneity

Fig. 1(a) as reported in [43], AA6061 alloy in a synthetic seawater slurry containing *Boswellia serrata* extract exhibited enlarged semicircle diameters as the flow rate increased from 4–12 $L\cdot min^{-1}$. This comparative evidence suggests that although physisorption dominates (ΔGads > –20 $kJ\cdot mol^{-1}$), the protective film remained relatively stable at higher flow rates, contrary to the common expectation of film erosion. The efficiency was limited to ~70% at 1000 ppm, indicating that weak adsorption energy restricts long-term stability under tribo-corrosive conditions.

Fig. 1(b) as reported in [44], *Alocasia odora* extract in 0.5 M HCl achieved a pronounced increase in Rct with concentrations of 2–8 $g\cdot L^{-1}$, reaching ~97% efficiency at the highest dosage. The strong agreement with the Langmuir isotherm ($R^2 \approx 0.991$) confirmed a dense monolayer adsorption. These findings underscore that the presence of multiple donor–acceptor sites (–OH, –COOH, –NH, π-systems) provides a high adsorption constant, suppresses ionic penetration (H^+/Cl^-), and explains the superior performance of *Alocasia odora* compared with other inhibitors in acidic media.

Fig. 1(c) according to [46], CFR–AA6061 composites immersed in 3.5% NaCl with *Aerva lanata* extract exhibited a significant increase in Rct, with ~85.9% efficiency at 600 $mg\cdot L^{-1}$. The disappearance of the inductive loop indicated film stabilization, while higher n-values reflected more uniform surface coverage. This suggests that adsorption proceeds through water molecule substitution,

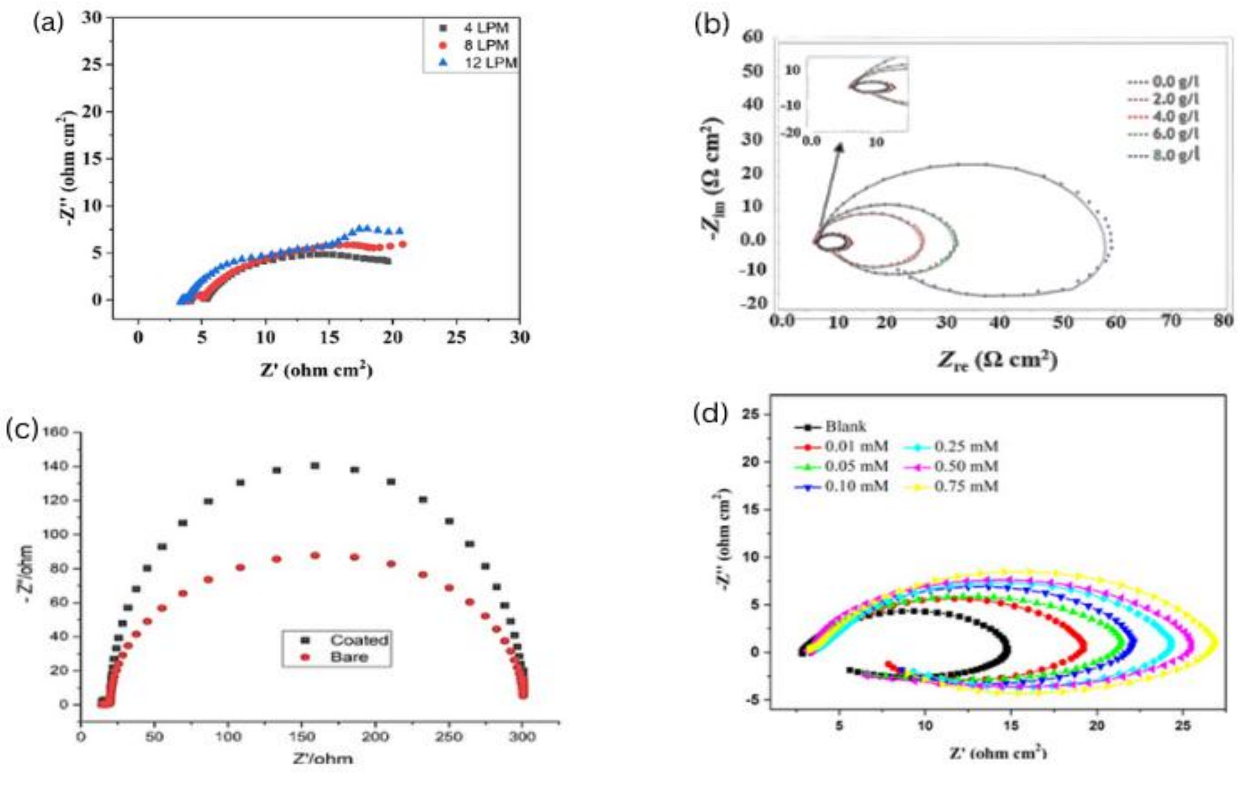

Fig. 1. Nyquist plots from EIS studies of AA6061 and its composites: (a) AA6061 in synthetic seawater slurry with *Boswellia serrata* inhibitor at different flow rates; (b) aluminium in 0.5 M HCl with *Alocasia odora* extract at 2–8 $g\cdot L^{-1}$; (c) CFR–AA6061 in 3.5% NaCl with and without *Aerva lanata* extract; and (d) 6061Al–SiC composite in 0.5 M HCl with glutathione at 0.01–0.75 mM. Data adapted from [43], [44], [46], [47]

Table 2. Reported PDP results for AA6061 aluminum alloy

No	Reference	Optimized parameters	Main result
1	[43]	Inhibitor Concentration, Slurry Flowrate, Temperature, Corrosion Current Density (I_{corr}). Inhibition Efficiency (IE%), Change in Corrosion Potential (E_{corr}).	The PDP shows that Boswellia serrata natural inhibitor at a concentration of 1000 ppm provides a maximum inhibition efficiency of 70% against corrosion of 6061 aluminum alloy at a temperature of 303 K and a flow rate of 4 L/min through a physical adsorption mechanism that is sensitive to increases in temperature and turbulence. are confidently correct.
2	[44]	Corrosion potential (E_{corr}), Corrosion current (I_{corr}), Tafel constants (βa and βc), Inhibition efficiency (η%).	PDP revealed that Alocasia Odora extract acted as a highly effective dominant cathodic inhibitor, reducing aluminum corrosion current by 98.97% at a concentration of 8.0 g/L in 0.5 M HCl solution.
3	[45]	inhibitor concentration, flow rate, and temperature.	The PDP successfully demonstrated that Boswellia serrata is an effective green inhibitor in reducing the corrosion rate of aluminum 6061, with the highest efficiency at high concentration, low flow rate, and low temperature. The inhibition mechanism was controlled by charge transfer, with contributions from adsorption of organic compounds on the metal surface.
4	[46]	Corrosion Potential (E_{corr}), Corrosion Current Density (I_{corr}), Inhibitor Efficiency (H%).	The PDP showed that *Aerva lanata* flower extract at 600 ppm concentration effectively inhibited the corrosion of carbon fiber reinforced 6061 aluminum laminate (FML) in 3.5% NaCl solution, with an increase in corrosion potential from -0.79 V to -0.77 V, a dcrease in corrosion current density from 0.001959 A/cm^2 to 0.0002335 A/cm^2.
5	[47]	Inhibitor concentration, Solution temperature.	PDP proved that Glutathione is a highly effective green inhibitor in reducing corrosion rate, with maximum effectiveness at 0.75 mM and 303 K temperature.
6	[48]	Pectin Inhibitor Concentration, Corrosive Media Temperature, Potential Scanning Range, Scan Rate, OCP Stable Time.	PDP showed that pectin acts as an effective mixed-type inhibitor, capable of significantly reducing the corrosion current density and corrosion rate through the formation of a protective film on the metal surface.

forming a compact organic layer that hinders both anodic and cathodic pathways. Compared with *Boswellia serrata*, *Aerva lanata* demonstrates greater robustness in neutral chloride environments due to the formation of a mechanically stable and adherent barrier.

Fig. 1(d) as reported in [47], glutathione (Gt) inhibited 6061Al–SiC corrosion in 0.5 M HCl. With concentrations ranging from 0.01–0.75 mM, Rp increased while Cdl decreased, yielding moderate efficiencies. Critical synthesis of these results indicates that physisorption remains the main mechanism, but partial coordination through N and S atoms contributes to adsorption. Nevertheless, performance declines at elevated temperatures, reflecting the weaker stability of peptide-derived inhibitors compared to plant-based extracts.

Synthesis. From this comparative review, it can be concluded that inhibitor performance is governed not only by adsorption energy but also by molecular functionality and interfacial film stability under specific environments. *Alocasia odora* exhibits the highest efficiency in acidic media (~97%) due to strong donor–acceptor chemistry and compact monolayer formation. *Aerva lanata* performs effectively in neutral chloride environments (~85.9%) by forming a robust and adherent film. Glutathione provides moderate protection in acidic solutions, with partial chemical interactions but thermal sensitivity. *Boswellia serrata,* while useful under low-flow conditions (~70%), is constrained by weak physisorption and poor mechanical stability. Overall, this synthesis highlights that the insights summarized here are drawn from existing literature and represent a critical review, not original experimental findings.

2.2. Evaluation of Potentiodynamic Polarization (PDP)

Potentiodynamic Polarization (PDP) is an electroanalytical technique used to evaluate the corrosion stability of materials by measuring the current flowing through electrodes when a potential is dynamically applied [49]. This technique can determine important parameters such as current corrosion, passivity, and corrosion rate in 6061 aluminum alloy [50].

As summarized in Table 2, Synthesis of PDP Findings from Multiple Studies Based on a cross-study review, the application of Potentiodynamic Polarization (PDP) on AA6061 aluminum alloy and its composites demonstrates that the effectiveness of natural inhibitors is governed by electrochemical parameters (E_{corr}, I_{corr}, Tafel slopes, Rp) in conjunction with environmental factors such as inhibitor concentration, temperature, flow rate, and the nature of the corrosive medium. These findings indicate that although all inhibitors provide measurable protection, the underlying inhibition mechanisms and physicochemical attributes of the molecules account for notable performance variations [43-48].

Experimental evidence has shown that *Boswellia serrata* extract achieves a maximum inhibition efficiency of approximately 70% at 1000 ppm, 303 K, and a slurry flow rate of 4 L/min [43]. The primary mechanism is physical adsorption, where a protective film develops on the alloy surface but tends to desorb under turbulent flow conditions. Compared with inhibitors tested under static acidic environments, its efficiency is relatively lower due to high sensitivity to hydrodynamic variations. The resinous constituents remain advantageous in semi-static systems, but their limitations suggest the need for hybridization with polymers or nanocomposite coatings. In practical terms, this inhibitor is relevant for low-flow systems such as cooling channels, though it is less suitable for marine environments with strong turbulence.

Conversely, *Alocasia odora* extract exhibited an inhibition efficiency of up to 98.97% at 8 g/L in 0.5 M HCl [44]. The dominant mechanism is cathodic inhibition, reflected by a drastic reduction in I_{corr} and a negative shift in E_{corr}. Its performance is markedly superior compared with other natural inhibitors across different media. This effectiveness is attributed to alkaloids and polysaccharides that enable strong interactions through hydrogen bonding and π-electron donation, thereby producing a compact and stable adsorbed film. Future studies should focus on validating long-term durability in real seawater conditions, as current data are limited to laboratory-based HCl tests. From a practical standpoint, *A. odora* represents one of the most promising alternatives to synthetic inhibitors in acid-based industrial applications.

Under jet impingement conditions, *Boswellia serrata* retained some protective effect, though efficiency decreased significantly with increasing temperature and flow rate [45]. The mechanism involves charge-transfer control through a fragile organic film susceptible to hydrodynamic stress. Its performance is inferior to that of *A. odora* in acidic media and *A. lanata* in chloride environments. Nevertheless, the resin continues to provide partial protection in semi-dynamic conditions. Future research should emphasize hybrid formulations (inhibitor plus coating) to enhance film stability under mechanical degradation. In practical terms, *B. serrata* remains applicable to heat exchangers or systems with moderate flow but is inadequate for highly turbulent operating environments.

Other findings demonstrated that *Aerva lanata* extract, at 600 ppm in 3.5% NaCl, increased E_{corr} from −0.79 to −0.77 V and reduced I_{corr} nearly tenfold, resulting in an inhibition efficiency of 85.9% [46]. The protective mechanism is compact adsorption of flavonoid and phenolic constituents, forming an adherent film on the composite surface. Its efficiency is nearly comparable to the strongest inhibitors tested in acidic conditions, indicating the versatility of its phytochemical composition. The key advantage lies in forming a dense film resistant to chloride ion penetration. Subsequent research should include long-term field testing in natural seawater to evaluate film stability under dynamic exposure. Practically, *A. lanata* is highly promising for protecting hybrid materials such as fiber-metal laminates (FML) in marine structures.

Glutathione has also been identified as a highly effective green inhibitor for 6061Al–SiC composites, with maximum efficiency at 0.75 mM and 303 K [47]. The proposed mechanism involves electron donation from the –SH group, simultaneously retarding both anodic and cathodic reactions. Unlike other natural inhibitors, Glutathione performs efficiently at very low concentrations. This property makes it an attractive candidate for low-dosage industrial applications. Future investigations should explore its stability in complex electrolytes and over extended exposure times. From a practical perspective, Glutathione offers substantial potential as an eco-friendly replacement for conventional synthetic inhibitors.

Finally, pectin has been confirmed as an effective mixed-type inhibitor for 6061Al–15%SiC(P) composites in acidic media, reaching efficiencies up to 95% [48]. The inhibition mechanism follows Langmuir adsorption isotherm, where chemisorption leads to protective film formation, significantly lowering I_{corr} and corrosion rate. Compared with resin-based inhibitors such as *B. serrata*, pectin demonstrates higher efficiency and improved film stability. This advantage arises from carboxyl groups (–COOH) that strengthen coordination bonding with aluminum surfaces. Future work should focus on developing polysaccharide-based bio-inhibitor composites for long-term applications. Practically, pectin provides a green, low-cost solution for protecting aluminum under mildly acidic conditions.

From this cross-study review it can be concluded that *Alocasia odora* is the most promising inhibitor for acidic environments, *Aerva lanata* excels in chloride-based systems particularly for FML,

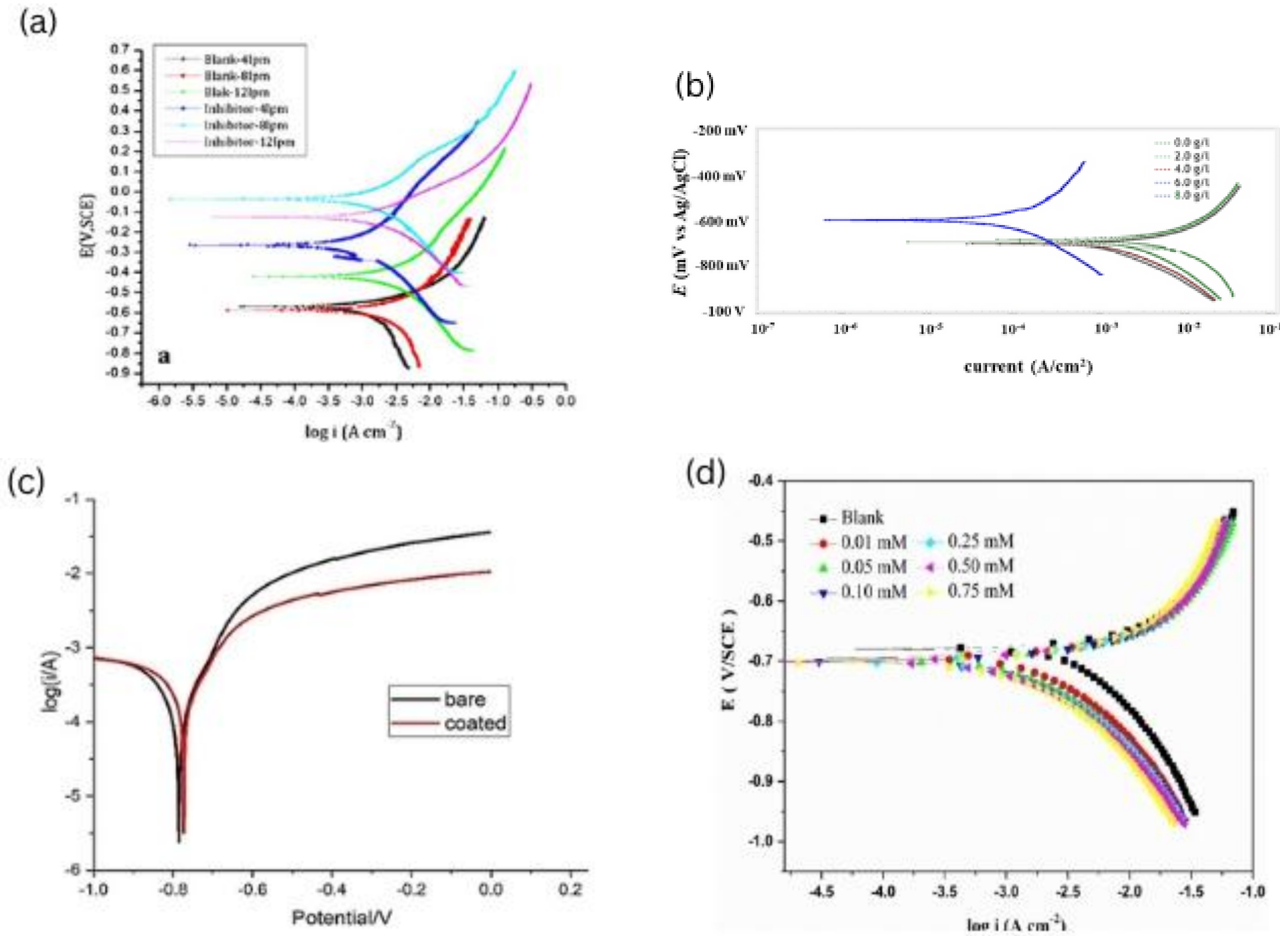

Fig. 2. Potentiodynamic polarization curves of AA6061 and its composites with bio-based inhibitors: (a) AA6061 in synthetic seawater slurry at 4, 8, and 12 L·min^{-1} with and without *Boswellia serrata* extract; (b) AA6061 in 0.5 M HCl with *Alocasia odora* extract at 2–8 g·L^{-1}; (c) CFR–AA6061 in 3.5% NaCl comparing bare and coated specimens with *Aerva lanata* extract; and (d) 6061Al–SiC composite in 0.5 M HCl with glutathione at 0.01–0.75 mM. Data adapted from [43], [44], [46], [47]

pectin is highly effective in mildly acidic conditions, while Glutathione demonstrates exceptional efficiency at very low concentrations. *Boswellia serrata* remains relevant in semi-static conditions but lacks stability under turbulence. Key determinants of inhibitor performance include the presence of functional groups (–OH, –COOH, $–NH_2$, –SH), π-electron density, and the molecular ability to form compact, stable films. Future research should emphasize integrating natural inhibitors with coating technologies and validating their performance through long-term seawater field trials to ensure sustainable industrial applications.

2.2.1 Potentiodynamic Polarization (PDP) Insights from literature on AA6061 and natural inhibitors

According to cross-study evaluations, the Potentiodynamic Polarization (PDP) results presented in Fig. A–D confirm that natural inhibitors can significantly reduce the corrosion rate of AA6061 alloy and its composites, although their effectiveness strongly depends on the medium and operating conditions.

Reports in the literature indicate that *Boswellia serrata* extract provides notable protection in synthetic seawater slurry at low flow rates, evidenced by reduced corrosion current density and a positive shift of the corrosion potential. However, its efficiency is limited to ~70% at 1000 ppm and decreases under higher hydrodynamic stress due to desorption of the physically adsorbed layer.

Other findings emphasize that *Alocasia odora* extract achieves the highest inhibition efficiency in 0.5 M HCl, reaching ~94% at 8 g·L^{-1}. The dominant mechanism involves suppression of the cathodic hydrogen evolution reaction and stabilization of the double layer, confirming its role as a cathodic-type inhibitor.

From the synthesis of available studies, it is evident that *Aerva lanata* shows strong affinity for carbon-fiber-reinforced AA6061 laminates in 3.5% NaCl solution. Treatment with this extract forms

Table 3. Reported SEM results for AA6061 aluminum alloy.

No.	Reference	Optimized parameters	Main result
1	[43]	Magnification, Sample preparation, Selection of observation area, Contrast and electron focus	SEM showed that *Boswellia serrata* inhibitor effectively formed a protective layer on the surface of aluminium 6061 which proved to be able to reduce morphological damage such as pits and craters due to corrosion-erosion in an artificial seawater slurry environment.
2	[44]	SEM observation parameters, purpose of observation, sample preparation, fixation conditions, magnification, features observed, type of information obtained.	SEM shows the formation of biofilms, the presence of pitting, the presence of *extracellular polymeric substances* (eps), and the surface area of aluminum alloy 6061 that is not completely covered by biofilms.
3	[45]	Before impingement, After impingement, After addition of 500 ppm BWS, Sand particles	SEM shows that *Boswellia serrata* inhibitor forms a protective layer that smooths the surface of aluminium 6061 and reduces erosion-corrosion damage, while sand particles do not degrade.
4	[46]	Analysing the surface morphology of FML, Comparison of three conditions, Effects of inhibitors.	SEM showed that the *Aerva lanata* extract coating significantly smoothed the FML surface and reduced corrosion damage.
5	[47]	Technical parameters, Immersion duration, Sample condition, Visual results (surface texture), Objective (protective layer validation)	SEM showed that the addition of 0.75 mM glutathione resulted in a smoother surface and minimal voids, indicating its effectiveness in forming a protective layer against corrosion.
6	[48]	Sample type, Surface preparation, Magnification, Exposure conditions, Morphology comparison, Correlation with EDX, Validation of inhibition efficiency.	SEM showed that the corroded AlMMC surface appeared rough and pitted, while the inhibited surface appeared smooth due to the formation of a protective film from pectin adsorption, indicating the effectiveness of pectin as a corrosion inhibitor and the presence of galvanic action without inhibitor.

a compact organic film at the interface, leading to polarization resistance enhancement and inhibition efficiencies of ~85.9–88%.

The results reported for glutathione indicate consistent, concentration-dependent inhibition of 6061Al–SiC composites in 0.5 M HCl, with efficiencies above 80% at 0.75 mM. The mechanism is primarily physisorption, reinforced by partial coordination of nitrogen, oxygen, and sulfur donor atoms at the metal–electrolyte interface.

From this comparative review, it can be concluded that *Alocasia odora* is the most promising candidate for acidic environments, *Aerva lanata* is effective in chloride-based multi-material systems, *Boswellia serrata* is suitable under low-flow marine conditions, and glutathione is relevant for aluminum composites in acidic media. This comparative evaluation highlights that the superior performance of each inhibitor arises from its distinct physicochemical characteristics, such as functional groups, adsorption strength, and resistance to flow-induced desorption, rather than from absolute inhibition efficiency values alone.

2.3. Evaluation of Scanning Electron Microscopy (SEM)

The working principle of the SEM tool is to utilize the backscattering of electrons (electron beam) on the surface of the object and take pictures by detecting electrons that appear on the surface of the object [51]. Advances in the use of Scanning Electron Microscopy (SEM) allow scanning large areas and collecting large amounts of data to obtain sample characteristics, including counting objects and collecting statistics on these objects, one of which is getting a size morphology image to determine size distribution [52]. SEM testing allows obtaining morphological and concentration images of mixed materials [53].

As summarized in Table 3, Based on a cross-study review, it can be concluded that natural inhibitors such as *Boswellia serrata, Alocasia odora, Aerva lanata*, glutathione, and pectin consistently form protective films on AA6061 aluminum alloy and its derivatives. This has been validated by SEM analysis, which shows smoother surfaces with reduced pits, and corroborated by electrochemical results (PDP and EIS) indicating decreased corrosion current density (I_{corr}), increased charge transfer resistance ($R_{(ct)}$) and decreased double-layer capacitance (Cdl). These findings demonstrate that inhibitor effectiveness is governed by three main factors such as molecular architecture and functional groups (–OH, –COO⁻, –SH, and π-electrons) that determine adsorption strength and film cohesion, the corrosive medium (HCl, NaCl, or marine environment, with galvanic risks in FML), and hydrodynamic load (static vs slurry/impingement) that dictates the stability of the protective layer against mechanical or thermal desorption [43-48].

From this review, it is evident that the linkage between experimental methods and inhibition mechanisms is increasingly clear. PDP tests reveal reduced I_{corr} and shift in E_{corr}, indicating the inhibition type (cathodic or mixed). EIS results display enlarged Nyquist semicircles and higher Bode phase angles, along with reduced Cdl, reflecting compaction of the interfacial layer. These outcomes are consistent with SEM observations showing protective films that cover active sites and reduce pitting. The convergence of these techniques strengthens the understanding that adsorption mechanisms generally follow Langmuir isotherms, with a critical distinction between chemisorption (strong, stable; pectin, glutathione, *A. odora*) and physisorption (weaker; Boswellia under tribo-corrosion conditions).

Cross-study comparisons underscore significant variations in performance. Pectin has been shown to be the most effective in mild acidic media, as its carboxylate polymer structure forms dense, adherent films through chemisorption, leading to higher Rct, lower Cdl, and suppression of micro-galvanic activity at the Al–SiC interface [48]. *Alocasia odora* exhibits high efficiency in 0.5 M HCl via predominantly cathodic inhibition, where oxygenated and alkaloid constituents reinforce chemisorption; however, the long-term stability of its film requires further verification [44]. In chloride-rich media (3.5% NaCl), *Aerva lanata* is effective in mitigating pitting and galvanic corrosion of AA6061–CFRP FML through polyphenol adsorption that blocks active sites [46]. Glutathione demonstrates strong performance at low dosages in HCl, as its –SH, $-NH_2$, and $-COO^-$ groups enable multisite coordination with Al/oxide surfaces, resulting in smoother morphologies with minimal voids on SEM, though its peak efficiency remains below that of pectin [47]. Meanwhile, Boswellia serrata is relevant under tribo-corrosion in seawater slurry environments. Its resinous terpenes form protective layers, but the physisorption-dominated mechanism makes it sensitive to flow and temperature, leading to reduced efficiency under turbulence due to mechanical and thermal desorption [43], [45].

This synthesis highlights that the most promising inhibitors vary according to the application context. In mild to moderately acidic environments, pectin is the primary candidate due to its stable film, while *Alocasia odora* serves as a strong alternative in 0.5 M HCl. In chloride and marine conditions, particularly for FML with galvanic risks, *Aerva lanata* offers the most effective protection. For harsh tribo-corrosion conditions, Boswellia serrata remains relevant despite moderate efficiency, making hybrid strategies (topcoat or sol–gel overlays) advisable. For Al–SiC composites requiring low dosages, glutathione provides favorable efficiency per concentration and potential synergy with polymeric inhibitors.

The physicochemical factors underpinning these differences include the density of donor electron sites (enhancing adsorption affinity to Al/oxides), molecular architecture (polymeric vs small molecules) affecting surface coverage and mechanical integrity, medium compatibility (acid vs chloride; galvanic susceptibility in FML), and hydrodynamic response (static vs impingement) influencing film desorption and wear. From this synthesis, it can be inferred that chemisorption yields more resilient protective layers under fluctuating conditions, while physisorption tends to deteriorate under flow and elevated temperatures.

2.3.1 Scanning Electron Microscopy (SEM) insights from literature on AA6061 and natural inhibitors

According to cross-study evaluations, the Scanning Electron Microscopy (SEM) observations presented in Fig. 3 illustrate the morphological evolution of AA6061 alloy and its composites in various corrosive environments, providing direct validation of the inhibition mechanisms previously indicated by electrochemical tests.

The reported results from several studies show that in Fig. 3(a), AA6061 specimens exposed to synthetic seawater slurry without inhibitors exhibited wear tracks and micro-pits typical of tribo-corrosion processes. With the addition of Boswellia serrata extract, the surface appeared smoother, although the protective film tended to peel off at higher flow rates. This observation is consistent with electrochemical data reporting a maximum inhibition efficiency of ~70% at 1000 ppm and 303 K under a flow rate of 4 $L \cdot min^{-1}$, decreasing under stronger hydrodynamic conditions due to desorption of the physiosorbed layer (weak adsorption, ΔGads close to the physisorption limit).

Other findings confirm that in Fig. 3(b), aluminum specimens immersed in 0.5 M HCl without inhibitor displayed localized attack and porous deposits, whereas those treated with *Alocasia odora* extract exhibited a smoother surface with significantly fewer pits. This morphology supports PDP

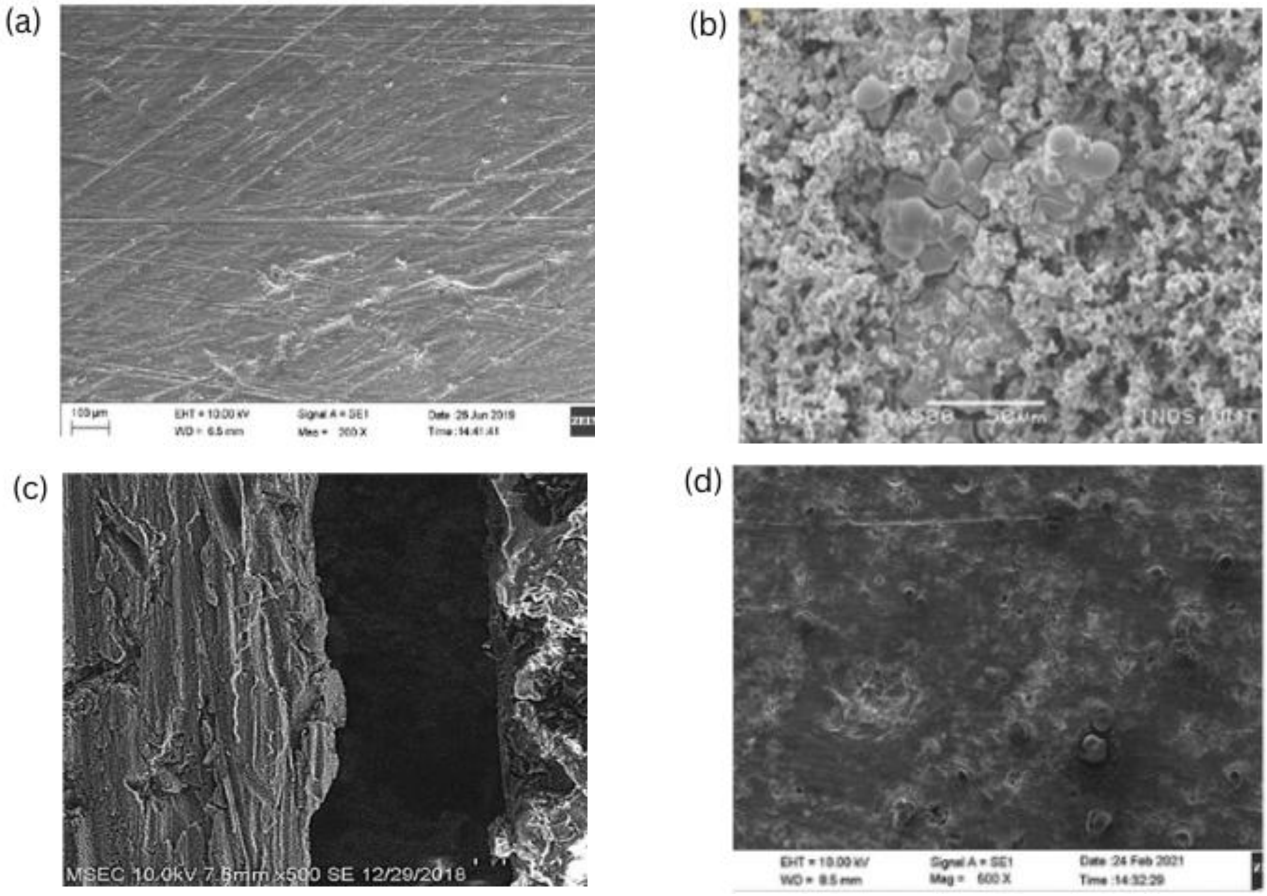

Fig. 3. Scanning Electron Microscopy (SEM) images of AA6061 and its composites with natural inhibitors: (a) AA6061 in synthetic seawater slurry at 4–12 L·min^{-1} with and without *Boswellia serrata* extract; (b) AA6061 in 0.5 M HCl with *Alocasia odora* extract at 2–8 g·L^{-1}; (c) CFR–AA6061 laminate in 3.5% NaCl comparing bare and coated specimens with *Aerva lanata* extract; and (d) 6061Al–SiC composite in 0.5 M HCl with glutathione at 0.01–0.75 mM. Data adapted from [43], [44], [46], [47]

results demonstrating its predominant role as a cathodic inhibitor by suppressing the hydrogen evolution reaction, achieving ~94% efficiency at 8 g·L^{-1}. Cross-study evidence also highlights that the presence of donor–acceptor groups (e.g., –OH, –COOH, –NH, and π-systems) enhances adsorption constants, facilitates the formation of a dense monolayer, and explains the superior performance of *Alocasia odora* in acidic media.

From the synthesis of the literature, it is evident that in Fig. 3(c), CFR–AA6061 laminates without inhibitor showed interfacial degradation and fiber detachment, whereas those treated with *Aerva lanata* displayed a more compact and strongly adherent interface. These morphological changes are consistent with EIS results, which indicate the formation of a dense organic film fitting the Langmuir isotherm, with inhibition efficiencies of ~85.9–88%. This comparative assessment suggests that the adsorption mechanism involves displacement of water molecules at the interface and possible hydrogen-bonding/π-interactions, both contributing to the stability of the protective film in neutral chloride media.

The results reported on glutathione indicate that in Fig. 3(d), 6061Al–SiC composites in 0.5 M HCl without inhibitor exhibited micro-pits and uneven corrosion products, whereas those treated with glutathione developed a more uniform surface covered by a thin adherent film. The protection mechanism is attributed to adsorption of nitrogen, oxygen, and sulfur donor atoms at the metal–electrolyte interface (physisorption reinforced by partial coordination), suppressing both anodic and cathodic reactions, with efficiencies exceeding 80% at 0.75 mM.

From this synthesis, it can be concluded that *Alocasia odora* provides the most effective morphological protection in acidic media (strong donor–acceptor interactions and compact monolayer formation), *Aerva lanata* is effective in neutral chloride-based systems (compact adherent organic film), Boswellia serrata performs under low-flow marine conditions but loses stability at higher hydrodynamics (weak physisorption prone to desorption), and glutathione is relevant for aluminum–

Table 4. Comparison of natural inhibitors for AA6061 Aluminum alloy

No.	Reference	Natural inhibitor	Corrosive medium, efficiency, and mechanism
1	[43]	*Boswellia serrata*	Artificial seawater with sand slurry (303 K, 4 L/min); ≈70% efficiency; physisorption with weakly adsorbed film, unstable under hydrodynamic flow; characterized by PDP, EIS, SEM.
2	[44]	*Alocasia odora* leaf extract	0.5 M HCl; 94.3% efficiency at 8 g/L (3 h of immersion); chemisorption with cathodic-dominant inhibition; characterized by PDP, EIS, SEM.
3	[45]	*Boswellia serrata*	Artificial seawater with sand slurry (303 K, 4 L/min); ≈70% efficiency; physisorption with weakly adsorbed film, unstable under hydrodynamic flow; characterized by PDP, EIS, SEM.
4	[46]	*Aerva lanata* flower extract	3.5% NaCl (FML–CFRP system); 88% efficiency at 600 ppm, room temperature (RT); chemisorption via polyphenol adsorption with pit suppression; characterized by PDP, EIS, SEM.
5	[47]	Glutathione (Gth)	0.5 M HCl (AA6061–SiC composite, 303 K); 80.1% efficiency at 0.75 mM; chemisorption through multisite coordination (–SH, $–NH_2$, $–COO^-$ groups); characterized by PDP, EIS, SEM.
6	[48]	Pectin	0.025 M HCl (AA6061–SiC composite); 95% efficiency; chemisorption with compact, adherent polymeric film; characterized by PDP, EIS, SEM, EDX.

SiC composites in acidic solutions (N/O/S donor adsorption with thermal sensitivity). This comparative review underscores that the superiority of each inhibitor is determined by its physicochemical features—molecular functionality, adsorption strength, and resistance of the protective film to flow-induced desorption—rather than by absolute inhibition efficiency values alone.

2.4. Comparative evaluation of natural inhibitors on AA6061

Corrosion protection using natural inhibitors has become an important focus in the development of corrosion mitigation strategies due to their environmentally friendly, biodegradable, and effective nature in forming a protective film on metal surfaces. Various organic compounds from plants, such as extracts of *Boswellia serrata, Alocasia odora, Aerva lanata*, pectin, as well as natural biomolecules such as glutathione, have been reported to inhibit the corrosion process through adsorption mechanisms and the formation of barrier films that isolate the metal from the corrosive medium.

As presented in Table 4, based on a cross-study review, it can be concluded that natural inhibitors applied to AA6061 alloys exhibit varying performance, as confirmed by PDP, EIS, and SEM results. Studies on *Boswellia serrata* report maximum efficiency of ~70% in artificial seawater with sand slurry (303 K, 4 $L·min^{-1}$). The underlying physisorption mechanism produces a thin and weak film that is easily desorbed under hydrodynamic stress, as reflected by smaller Nyquist semicircles and SEM images still showing evident pits.

In the case of *Alocasia odora*, it has been reported that in 0.5 M HCl the inhibitor achieves ~94.3% efficiency at 8 $g·L^{-1}$ after 3 h of immersion. These results confirm that chemisorption with predominantly cathodic inhibition forms a more stable protective film, as supported by PDP, EIS, and SEM data. Studies on *Aerva lanata* have demonstrated that in chloride media (3.5% NaCl, FML–CFRP system), the inhibitor achieves up to 88% efficiency at 600 ppm under room temperature. These findings suggest that polyphenolic constituents promote chemisorption, blocking active sites and suppressing pitting, as verified by PDP, EIS, and SEM analyses. Other reports on glutathione indicate its effectiveness on AA6061–SiC composites in 0.5 M HCl (303 K), even at low dosages, with efficiencies reaching ~80.1% at 0.75 mM. From this synthesis, it can be inferred that the –SH, $–NH_2$, and $–COO^-$ groups enable multisite coordination, reinforcing the protective layer in line with PDP, EIS, and SEM evidence.

Studies on pectin consistently report that in 0.025 M HCl with AA6061–SiC composites, inhibition efficiency can reach ~95%. This comparative review indicates that compact and adherent polymeric films formed through chemisorption markedly enhance Rct, reduce Cdl, and minimize pits on SEM, corroborated by EDX validation. From this synthesis, it can be concluded that although all natural inhibitors reduce the corrosion rate of AA6061, pectin represents the most promising candidate in mild acidic media, *Alocasia odora* is highly effective in HCl environments*, Aerva lanata* is suitable for chloride/FML systems, glutathione demonstrates favorable efficiency at low dosage, and Boswellia serrata remains relevant under tribo-corrosion despite reduced performance under high flow conditions.

Critical insights from this comparative review also highlight several research gaps that warrant further investigation. The long-term durability of natural inhibitor films has rarely been evaluated, since most available studies are restricted to short-term immersion; cyclic testing under variable flow, fluctuating temperatures, and complex multi-ion environments remain scarce. Advanced characterization techniques such as XPS, ToF-SIMS, Raman, and AFM are still underutilized, even though they are essential for providing deeper insights into the chemical composition, thickness, and homogeneity of protective films. Galvanic phenomena in AA6061-based fiber-metal laminates and composites have not been comprehensively addressed; in this regard, local potential mapping with SKP or SECM is required to identify galvanic hot-spots that remain invisible to global electrochemical measurements. Hydrodynamic stability continues to be a critical challenge, particularly for physisorption-based inhibitors such as *Boswellia serrata*, whose weakly adsorbed films are easily removed under flow; hybrid strategies combining natural inhibitors with additional protective layers such as sol–gel or topcoats should be explored to improve flow resistance. Finally, synergistic approaches remain underexplored: combining polymeric inhibitors (e.g., pectin) with small molecules such as glutathione and optimizing their dosage could potentially yield more robust and cost-effective corrosion protection.

3. Conclusions

Based on this cross-study review, it can be concluded that natural inhibitors applied to AA6061 alloys, and their composites exhibit diverse performance depending on the corrosive medium, adsorption mechanism, and molecular structure. Literature reports consistently show that Boswellia serrata provides only moderate protection (~70%) in seawater slurry, where physisorption forms weak films that are easily desorbed under hydrodynamic stress. In contrast, *Alocasia odora* achieves superior inhibition (~94.3% in 0.5 M HCl) through chemisorption with predominantly cathodic inhibition, while *Aerva lanata* demonstrates ~88% efficiency in chloride-based FML systems via polyphenolic chemisorption. Glutathione offers favorable protection (~80% at 0.75 mM) even at low dosage through multisite coordination, and pectin consistently delivers the highest performance (~95% in mild acidic media) by forming compact and adherent polymeric films. Mechanistic comparisons across these inhibitors highlight that chemisorption-based systems generally outperform physisorption-based systems. While Boswellia serrata suffers from unstable adsorption, Alocasia, Aerva, Glutathione, and Pectin form denser and more durable protective layers. The evidence from PDP, EIS, and SEM analyses confirms that donor–acceptor functionalities (–OH, –COOH, –NH, –SH, π-systems) and multisite coordination play critical roles in determining adsorption strength, film stability, and corrosion inhibition efficiency. This synthesis demonstrates that inhibition performance is not defined solely by efficiency values, but by the interplay between molecular structure and environmental conditions. From this synthesis, several critical insights emerge regarding future research directions. The long-term durability of inhibitor films remains poorly understood, as most studies are limited to short-term immersion. Advanced characterizations (XPS, ToF-SIMS, Raman, AFM) are still underutilized for probing interfacial chemistry, while galvanic interactions in AA6061-based FMLs require mapping with SKP or SECM. Hydrodynamic stability remains a significant challenge for physisorption-based inhibitors such as *Boswellia serrata*, suggesting the need for hybrid strategies combining natural inhibitors with sol–gel or polymeric coatings. Moreover, synergistic approaches such as combining polymeric inhibitors like pectin with small molecules such as glutathione remain underexplored despite their potential to deliver robust, durable, and cost-effective protection. In practical terms, this comparative review underscores the promise of bio-derived inhibitors as sustainable and environmentally friendly alternatives to toxic synthetic inhibitors. Applications in automotive, marine, and aerospace industries can benefit from the integration of natural inhibitors into existing protection systems, particularly when combined with advanced coatings and hybrid strategies. This review uniquely synthesizes comparative evidence from PDP, EIS, and SEM studies, providing not only a consolidated knowledge base but also a roadmap for advancing green corrosion inhibitors toward scalable industrial implementation.

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