



*Mini review*

## **An overview of sustainable green inhibitors for aluminum in acid media**

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**Abstract:** Metal corrosion is a significant and growing area of study in industrial problems, which has found productive research ground in the field of green chemistry. In the last 10 years, green chemistry has been highlighting the importance of safeguarding human as well as the environmental well-being, in an economically advantageous way aiming at keeping away from reducing waste hazardous toxins, and pollutants. The era of metal degradation, commonly faced due to the usage of hazardous chemicals became very relevant and useful in the research area of chemistry. Even though several experiments have been conducted and, several research articles were published on this topic of nature-friendly green and clean inhibitors still there are yet a lot of things to be explored in this field for sustainable eco-friendly existence of human and natural interconnected existence. The main aim of the study is to provide a summary and describe the past authentic research that accounted in the research literature to employ eco-friendly corrosion inhibitors, especially extraction from leaves, stems, seeds, and fruits of the plants for aluminum alloy in acid solutions in the past decade. Weight loss and electrochemical approaches are among the most often utilized methods to measure corrosion rate and to evaluate the effectiveness of green corrosion inhibitors. The relevance of the area prompted the further study, leading to a large number of substances being evaluated.

**Keywords:** green inhibitor; aluminum; acid; adsorption; green solvent

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**Abbreviations:** AFM: Atomic force microscopy; EDS: Energy dispersive spectrometry; EFM: Electrochemical frequency modulation; EIS: Electrochemical impedance spectroscopy; SEM: Scanning electron microscope; PDP: Potentiodynamic polarization; SES: Scanning electron study; WL: Weight loss; CR: Corrosion rate; h: Hour; DW: Distilled water

## 1. Introduction

In 2012, Member States resolved to initiate a process to establish a set of SDGs (Sustainable Development Goals) based on the Millennium Development Goals and address the post-2015 development agenda at the UN Conference on Sustainable Development, often identified as Rio 20. By 2030, the SDGs seek to make a wealthier, equitable, and secure world. The 2030 Docket for Sustainable Development has 169 goals and 17 SDGs. These goals are the consequence of a new consultation mechanism that brought together national administrations and millions of people from across the world to explore and agree on a 15-year global path to sustainable development. These 17 goals are to be achieved by 2030. Thing 15.2 underlines the significance of biodiversity in a sustainable future. The part of biodiversity and ecosystem services has to be conceded in social, economic, financial, and environmental programs, along with their centrality to agriculture, fisheries, forestry, tourism, energy and mining, structure, manufacturing, and processing, and health diligence. This knowledge will be basic to achieving the goal. Human conditioning has led the resources to deplete. The agenda of sustainable development is on topmost precedence in the whole world. The utilization of natural resources must be cut back to achieve sustainable development. These social, economic, and environmental objects must be fulfilled. We cannot sustain development if we fall suddenly to maintaining an equilibrium of social, economic, and environmental objects. Natural resources must be guarded despite severe human activity then the role of educating and education for sustainable development is pivotal. Operation of resources was essential in the people around the world as we Indians find its evidence in our ancient literature like the Vedas. Sustainable development and environmental management depend on individual acts. The Vedic wisdom of India says that the terrain must be sustained and guarded. The exploitation of natural coffers degrades the environment. The consequences will be poverty and hunger, pollution, resource reduction, and a drop in the weal of the population. To safeguard the earth and our actuality we must adopt ways of co-existence in harmony with nature.

The continued processing of fossil-based feedstocks in the creation of chemical products including fuels and volatile organic solvents has aroused severe concerns about air quality degradation, safety, and health risks. As a result, various attempts are being undertaken to decrease the use of harmful compounds in chemical processes, as well as to reduce or eliminate waste. In both industry and academics, switching from commonly used fossil-based solvents to greener ones generated from renewable resources is a significant approach for achieving sustainability and safer and clean chemical processes.

It has become increasingly important in recent years to consider the long-term interests of present and future generations while pursuing sustainable development. Human-ecosystem equilibrium as a target aim of sustainability has been proposed, and sustainable development as an integrated strategy and a series of time-based processes that take us to that goal [1]. Environmental sustainability is closely related to green Chemistry. This term was first used in 1990 by the US Environmental Protection Agency (EPA) to encourage novel chemical technologies, and decrease or eradicate the utilization or

creation of unsafe chemicals in the design, synthesis, and use of chemical goods. Basic scientific methodologies, such as those found in solvents, catalysis, synthetic methodology, analytical development, and the creation of safer chemicals with a raised awareness of their environmental effect are all included in the green chemistry movement's approach to protecting human health and the environment. Green chemistry and sustainability are based on the use of renewable raw materials in various industrial applications, according to this perspective. There has been an increase in interest in renewable raw materials as a result of nature's wide variety of chemical compositions.

Consequently, their interactions with their external conditions, corrosion is a normal occurrence in which alloys as well as metals effort to return to a more stable "thermodynamic state". Corrosion is costly owing to the loss of materials or their qualities, which results in lost time during maintenance, structural collapse, and shutdowns, which may be hazardous and cause damage in certain conditions [2]. The issue of corrosion is becoming more important as metals and alloys are used more often in contemporary life. One of the most significant non-ferrous metals, aluminum is used extensively in the food and packaging industry. Aluminum is a great conductor of electricity because of its excellent properties. Aluminum has mostly replaced copper because of this characteristic and several other inherent properties. This implies that aluminum is a thermodynamically reactive metal, second only to magnesium among major engineering metals [3]. Aluminum and its alloys are extremely resistant to corrosion in a wide range of conditions. In aqueous solutions, aluminum is known to behave passively. Metal corrosion has been linked to processes including metal ion move to the oxide/metal interface, oxygen ion and metal ion transfer to the solution/oxide interface, transferring an electron from the metal to acceptor species in solution, migration of ion in the oxide film, and all of which are associated with the passivating surface oxide film [4].

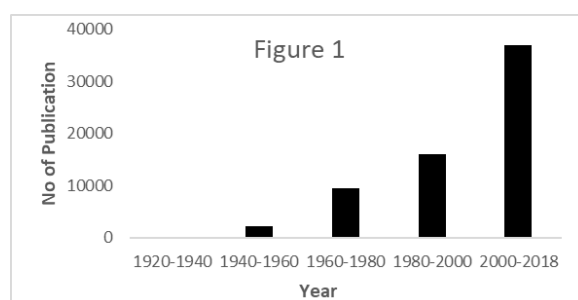
Typically, hydrochloric acid solutions are employed for pickling aluminum alloys as well as electrochemical and chemical etching operations, which often result in significant dissolution. For the removal of unwanted and undesirable scales, acid solutions are mainly used. In the cleaning process in industries generally, sulfuric and hydrochloric acid solutions are employed. As a result, several efficient inhibitors are applied to regulate metal dissolving and acid absorption [5]. Inorganic or organic molecules that adsorb on the metallic surface and separate it from its external environment to block the process of oxidation-reduction may be used in the corrosion inhibition procedure [6].

In acid media, nitrogen-containing organic compound means amines, alkaloid, quinine, nicotine, strychnine, papaverine, oxygen-containing functional groups such as ketone, aldehyde, ester, acetylenic compounds, and sulfur-containing compounds are used as corrosion inhibitors. Several studies have discovered nitrogen inhibitors number for metal and alloy corrosion inhibition in acid media.

Those organic inhibitors that include nitrogen are very effective at preventing the formation of metal in acidic solutions [7–13]. Furthermore, a variety of heterocyclic synthetic compounds were identified as corrosion inhibitors, and investigation into these molecules is currently ongoing [14]. Although several synthetic compounds exhibited strong anticorrosive performance, there was widespread concern about their toxicity to humans as well as the environment during the compound's synthesis or usage [15,16]. Typically, the reported inhibitors utilized in industries are very poisonous and environmentally dangerous.

Green inhibitors are gaining popularity in the corrosion meadow these days because of their biodegradability, safety, renewability, as well as ecological compatibility. These include amino acids [17], alkaloids [18], polyphenols [19], and plant extracts [20], which are widely disseminated

and have minimal economic value, as well as byproducts of agro-industrial operations and agricultural waste. Chitosan oligomers are soluble over a wide pH range from acidic to basic ones. On the contrary chitosan derivatives with higher molecular weight are only soluble in acidic aqueous even at high deacetylation degrees. This is the favorable property for corrosion inhibition, and therefore, chitosan derivatives are nowadays used as corrosion inhibitors for metal dissolution [21–24]. Corrosion inhibitors that are safe for the environment may be found in natural materials because most of their extracts contain necessary elements like oxygen, nitrogen, carbon, and sulfur, which are active in organic molecules and aid in the adsorption of such molecules on alloys or metals to create a film that protects the exterior sides and prevents corrosion. N, S, and O-containing chemical substances are found in their barks, leaves, fruits, and seeds and some of them are efficient inhibitors of metal and alloy corrosion in a variety of severe settings. The quantity of adsorbed inhibitors on the metal surface determines the inhibition efficacy. As shown in Figure 1, the documentation on the subject of green corrosion inhibitors for metal surfaces is primarily active. Figure 1 shows the published research articles on the topic of green corrosion inhibition that were found using a SciFinder literature survey [25]. The increasing rate of publication indicates an exponential trend. As a result, the current review paper discusses the application of prospective green “eco-friendly inhibitors” on the surface of aluminum metal in acidic solutions as effective corrosion inhibitors.



**Figure 1.** Year-wise publication.

## 2. Experimental

A general description of the method used by research workers to determine corrosion rates is as follows.

### 2.1. Weight loss

The traditional mass loss technique may be utilized to assess the corrosion rate. Using this approach, the mass loss of metal owing to exposure to corrosive fluids for a certain period and computing the variation in weight before and after immersion may be determined. For the immersion period, acid solution with and without inhibitors was used to immerse aluminum alloy/metal test specimens. Extraction from the plants was used as an inhibitor having appropriate concentration. The specimens were hanging with aid of a glass hook. After a certain period of exposure, specimens were taken out and washed with a cleaning solution by washing them twice with double distilled water, drying them, and then weighing it, corrosion products were removed. The mass loss was determined

by comparing the pre-and post-exposure weights of the specimens. The following formulae (1) to (3) were used to compute the rate of corrosion, surface coverage degree ( $\Theta$ ), and inhibition efficiencies: the corrosion loss in the uninhibited system is represented by  $W_u$ , while  $W_i$  is represented as corrosion loss is inhibited.

$$CR \text{ (mpy)} = \frac{534W}{DA t}, \quad (1)$$

$$\eta\% = \frac{W_u - W_i}{W_u} \times 100, \quad (2)$$

$$\Theta = \left( \frac{W_u - W_i}{W_u} \right), \quad (3)$$

where  $D$  represents the density of metal specimen,  $W$  represents the metal mass loss in grams, metal sample surface area in inches square is represented by  $A$  and ‘ $t$ ’ represents a time for immersion in hours.

When electrochemical corrosion begins, the current flowing between the cathode & anode creates polarization, which is a change in the electrode potential.

## 2.2. Potentiodynamic polarization

A sample is subjected to polarization procedures to alter its current or potential, which are then recorded. There are two ways to do this: either using AC (alternating current) or DC (direct current) [5]. The following are a few of the most widely used and essential approaches.

Tafel Extrapolation: anodic and cathodic processes in an electrochemical cell are shown by Tafel curves, a current potential diagram. Working electrode (metal sample) potentials are adjusted at a precise pace and the resultant current response is recorded in this approach. A total current is produced by the simultaneous anodic and cathodic reactions, which is signified by a curve line. The logarithmic Tafel plot’s linear sections are inferred to create an intersection that offers a point of reference that represents the “corrosion rate” and inhibition efficacy calculations based on Eqs (4) and (5), respectively.

$$CR \text{ (mpy)} = \frac{(0.13 \times i_{corr} \times E.W.)}{n \times d}, \quad (4)$$

where the equivalent weight of the aluminum metal in grams is denoted by ‘E.W.’, corrosion current density ( $\mu\text{A}$ ) by ‘ $i_{corr}$ ’, electron number by ‘ $n$ ’, metal density by ‘ $d$ ’ and metric, and the time conversion factor are 0.13.

$$\eta(\%) = \left[ \frac{i_{corr}(u) - i_{corr}(i)}{i_{corr}(u)} \right] \times 100, \quad (5)$$

where corrosion current densities values with  $i_{corr}(i)$  and without inhibitor  $i_{corr}(u)$  were calculated using Eq (5), whereas ( $\eta\%$ ) percentage efficiency (percent) was derived from the graph.

### 2.3. LPR (Linear polarization resistance)

This approach is non-destructive [26], has rapid application, may be utilized in the field with portable equipment [27], and is the most employed electro-chemical method [28]. The LPR principle is to spread the corrosion equilibrium over the metal surface by using a modest perturbative DC electrical pulse. The equilibrium's reaction to this perturbation is assessed in comparison to a source half-cell [29]. At the free corroding potential, the polarization  $\Delta E/\Delta i$  potential current density curve slope. The Stern-Greay approach, in which the cathodic and anodic Tafel slopes may be empirically determined from actual polarization plots, can be used to connect the LPR to the corrosion current.

The inhibitory efficiency has been derived from the observed polarization resistance value with the following formula:

$$\eta(\%) = \left[ \frac{R_p' - R_p^0}{R_p'} \right] \times 100, \quad (6)$$

where polarization resistance  $R_p'$  and  $R_p^0$  are with and without inhibitor, correspondingly.

### 2.4. EIS (Electrochemical impedance spectroscopy)

This is a potent method that may be used to evaluate coatings in corrosion studies. Useful information is gained by using this method to determine the effectiveness of an inhibitor. An AC voltage (in potentiostatic EIS case) or current (in galvanostatic EIS case) is given to the system under studies to get a response in voltage (current) or current (voltage) form as a frequency function. Using potentiostat-galvenostat and a frequency response analyzer, this procedure may be conducted in a three-electrode setup (FRA) [30]. On the basis of the Nyquist plot shape, an AC voltage with minor perturbations of 5 mV to 10 mV is given in the system throughout a frequency range generally beginning from 100 kHz to 10 mHz, an equivalent circuit comprises information on  $R_s$  ("solution resistance"),  $C_{dl}$  ("double-layer capacitance"), and  $R_{ct}$  ("charge transfer resistance") to represent the electrochemical cell including the metal sample, electrolyte medium, as well as adsorbed inhibitors. As inhibitor concentrations increase, the  $R_{ct}$  value increases, whereas the  $C_{dl}$  value decreases [31].  $R_{ct}$  values have been evaluated by deducing the high from the low-frequency impedance, as shown below [32]:

$$R_{ct} = Z \text{ (at low frequency)} - Z \text{ (at high frequency)}. \quad (7)$$

The following equation was used to compute the values of  $C_{dl}$  at  $f_{max}$  frequency, where the imaginary impedance component is maximum ( $Z_{max}$ ) [33]:

$$C_{dl} = \left[ \frac{1}{2\pi f_{max}} \right] \left[ \frac{1}{R_{ct}} \right]. \quad (8)$$

By using Eq (9) the IE percent (percentage inhibition efficiency) from the  $R_t$  values [34]:

$$\eta(\%) = \left[ \frac{R_{ct(inh)} - R_{ct}}{R_{ct(inh)}} \right] \times 100, \quad (9)$$

the  $R_{ct}$  in the absence and presence of the inhibitor values is represented by  $R_{ct}$  and  $R_{ct(inh)}$ , correspondingly.

## 2.5. Scanning electron microscope

It is a kind of microscope that utilizes a centered electron beam to produce pictures of a specimen. Several signals may be recorded that provide information regarding the specimen's surface geography and composition when electrons contact atoms in the sample. When scanning the electron beam using a raster pattern, the received signal and the beam's position are combined to generate an image. One nanometer resolution is possible using SEM. High vacuum, low vacuum, moist, and high-temperature specimens may all be inspected. Atoms energized by an electron beam emit secondary electrons, the most common kind of electron. This plume is mostly covered by a sample on a flat surface, however, on a tilted one the plume is partially revealed and most secondary electrons are released. When the specimen is examined and the "secondary electrons" are seen, a picture of the surface topography is created [35].

For SEM examination, aluminum samples were immersed in the acid solution for a predetermined period. A nitrogen stream was used to dry the samples after they were removed from the solutions and cleaned with deionized water. To further understand the surface's morphology, SEM was used.

## 3. Discussion

Natural materials and plant extracts may be used as corrosion inhibitors, and this research aims to gather a bibliography of relevant studies. The necessity of emphasizing the weak spots and insufficiencies in the green inhibitors area as constructive criticism to re-analyze the literature and recognize future work in the subject that often lacks rationality is emphasized in particular. Table 1 contains a list of all the extracts that were used as green corrosion inhibitors and would be discussed in the study. There is a table in the published work of the previous ten years that describes their respective natural source, extraction solvent, protected metal & corrosive environment, the inhibition efficacies, and other relevant information.

**Table 1.** References and results of research done by the author.

Ref.	Inhibitors	Extract	Metal	Solutions	Methods	Inhibition efficiency (%)	Adsorption isotherms
[36]	<i>Tender arecanut seed (TAS)</i>	DW, Soxhlet 6 h	Al	0.5 M HCl	WL, polarization, EIS	94.44	Langmuir
[37]	<i>Dry arecanut seed</i>	DW, Soxhlet 7 h	Al	0.5 M HCl	WL, polarization, probe method	94.45	Langmuir
[38]	<i>Trigonella foenum graecum seed (Fenugreek)</i>	DW, 24 h	Al 99.2%	1 M HCl	WL, 308–338 K, PDP, EIS, HPLC	86.53	Langmuir
[39]	<i>Milk thistle leaves</i>	DW, Soxhlet 7 h	Al AA7051	0.01 M HCl	WL, PDP	86.41	Langmuir

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Ref.	Inhibitors	Extract	Metal	Solutions	Methods	Inhibition efficiency (%)	Adsorption isotherms
[40]	<i>Coriandrum sativum</i> leaves	DW	Al 99.61%	1 M H <sub>3</sub> PO <sub>4</sub>	EIS, PDP, SEM, 303–333 K	72.75	Langmuir
[41]	<i>Irvingia gabonensis</i> plant	DW, 24 h	Al	1 M HCl	WL, temperature	97.36	Langmuir
[42]	Cantaloupe juice & seed	DW	Al alloy 32177	0.5–1.5 M HCl	WL	92.75, 71.60	Langmuir, Temkin
[43]	Date palm leaves	DW, 3 h, 253 K	Al 98.8%	1 M HCl	WL, 293–323 K, SEM, EDS	87.8	Langmuir
[44]	<i>Carcia papaya</i> seeds	DW	Al 98.84%	2 M H <sub>2</sub> SO <sub>4</sub>	PDP, EIS, SEM	96.70	Langmuir
[45]	<i>Melia azedarach</i> leaves	DW, 6 h	Al 99.99%	2 M HCl	WL, PDP, EIS	86.2	Langmuir
[46]	Olive seeds	DW, 24 h	Al 98.63%	1 M HCl	WL, 303–313 K, EIS, SES	98.86	Langmuir
[47]	<i>Tinosporacordiofolia</i> stems	DW, 5 h,	Al 98.84%	H <sub>2</sub> SO <sub>4</sub> (PH = 3)	PDP, 303–323 K, EIS, FT-IR	88.02	Langmuir
[48]	<i>Calotropis gigantea</i> leaves	DW	Al 98.02%	0.4–0.6 M HCl	WL, 313–333 K	84.31	Langmuir, Freundlich, Temkin
[49]	<i>Cissus populnea</i> stem	DW	Al 99.8%	0.5 M HCl	WL	72.63	Langmuir, Freundlich, Temkin, Flory-Huggins
[50]	<i>Bacopa monnieri</i> leaves	DW, 5 h	Al 99.54%	0.75–1.25 M HCl	WL, PDP, EIS	91.85	Langmuir
[51]	<i>Tulsi (Ocimum scantum)</i> leaves	DW, 1 h	Al 99.54%	0.75–1.25 M HCl	WL, 313–333 K, PDP, EIS	85.17	Langmuir
[52]	<i>Azadirachta indica</i> leaves	DW, 3 h	Al A-63400	0.5 M HCl	WL, 313–333 K	84.96	Langmuir, Freundlich
[53]	Cumin seeds	DW, 2 h	Al 99.54%	1 M HCl	WL, PDP, EIS, SEM	88.39	Langmuir
[54]	<i>Calotropis gigantea</i> leaves	DW	Al 98.02%	0.4–0.6 M HCl	WL, polarization	84.31	Freundlich
[55]	Aloe Plant	DW	Al 95.2%	0.5 M HCl	PDP, EIS	80.01	Freundlich
[56]	Bitter Kola	DW	Al 98.76%	0.5 M HCl	WL, 303–333 K	82.96	-
[57]	<i>Sida acuta</i> stem	DW	Al-Cu-Mg Alloy 95.5%	0.5 M HCl	WL	93.63	-

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Ref.	Inhibitors	Extract	Metal	Solutions	Methods	Inhibition efficiency (%)	Adsorption isotherms
[58]	<i>Beet root</i>	DW	Al 95%	H <sub>2</sub> SO <sub>4</sub> (PH = 3)	WL, influence of Zn, PDP, EIS, FT-IR, fluorescence	98.0	-
[59]	<i>Yellow colour ripe arecanut husk</i>	1% HCl, Soxhlet 24 h	Al A-63400	0.5 M HCl	WL, 303–323 K, polarization, EIS	83.33	Langmuir
[60]	<i>Spondias mombin leaves</i>	0.5 M H <sub>2</sub> SO <sub>4</sub> , reflux 3 h	Al	0.5 M H <sub>2</sub> SO <sub>4</sub>	WL, 30–60 °C, KI	80.3, 95.1(with KI)	Langmuir
[61]	<i>Murraya Koengii leaves (Curry)</i>	HCl	Al	HCl medium of pH 3 solution	polarization, EIS	91.79	Langmuir
[62]	<i>Newbouldia laevis leaves</i>	HCl, 3 h	Al AA5052	0.5 M HCl	WL, 298–313 K, PDP, SEM	87.0	Langmuir, Temkin
[63]	<i>Piper guineense seed</i>	1 M HCl, reflux 3 h	Al 98.47%	1 M HCl	WL, 303–353 K	95.34	Langmuir
[64]	<i>Carica papaya leaves</i>	1 M H <sub>2</sub> SO <sub>4</sub> , 24 h	Al 98.94%	1 M H <sub>2</sub> SO <sub>4</sub>	WL, 303–323 K, SEM, FT-IR	70.0	Langmuir
[65]	<i>Papaya peel fruit (Carica Papaya)</i>	1 M HCl, reflux 5 h	Al alloy	1 M HCl	Polarization, EIS, SEM	98.1	Langmuir
[66]	<i>Aspilia africann leaves</i>	HCl, 3 h	Al AA3003	0.4 and 0.5 M HCl	WL, polarization, EIS	95.0	Langmuir, Temkin
[67]	<i>Nipah palm (Nypa fruticans)</i>	2 M HCl	Al 99.98%	2 M HCl	WL	51.43	Langmuir
[68]	<i>Cinodosculus chayamansa leaves</i>	HCl, 3 h boil	Al 98.84%	1 M HCl	WL, additives KI	58.0	Langmuir
[69]	<i>Hibiscus sabdariffa</i>	1 M H <sub>2</sub> SO <sub>4</sub> , boiled for 3 h	Al Pure	0.5 M H <sub>2</sub> SO <sub>4</sub>	WL, PDP, EIS, 298–333 K	94.0	Langmuir
[70]	<i>Azadirachta indica leaves</i>	HCl, 2 h	Al 93.10%	1.85 M HCl	Gasometric RT, SEM	-	Langmuir, Freundlich, Frumkin, Temkin
[71]	<i>Terminalia ivorensis</i>	0.5 M HCl, 3 h	Al AA8011	0.5 M HCl	WL	89.56	Temkin
[72]	<i>Veronia amygdalina</i>	HCl, 2 h	Al 99.0%	2 M HCl	Gasometric	99.9	Temkin

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Ref.	Inhibitors	Extract	Metal	Solutions	Methods	Inhibition efficiency (%)	Adsorption isotherms
[73]	<i>Camellia sinensis</i> (green tea)	0.5 M HCl	Al 99.0%	0.5 M HCl	WL	90.57	Freundlich
[74]	<i>Orange seed</i>	HCl, reflux 3 h	Al	1 M HCl	WL	38.37	-
[75]	<i>Azadirachta indica</i>	HCl	Al 99.54%	0.75–1.25 M HCl	WL, PDP, EIS, SEM	96.41	-
[76]	<i>Azwain seed</i>	-	Al	0.5 M HCl	WL, polarization, EIS, SEM	90.0	Langmuir, Frumkin
[77]	<i>Andrographis paniculate plant</i>	-	Al 98.8%	HCl medium of pH = 3 solution	Polarization, EIS, 303–323 K, SEM	91.7	Langmuir
[78]	<i>Ajowan plant</i>	-	Al	0.5 M HCl	WL, polarization, EIS	80.98	Langmuir
[79]	<i>Capparis decidua</i>	-	Al 99.99%	1 M HCl	WL, polarization, EIS, SEM	88.2	Langmuir, Temkin
[80]	<i>Jasminum nudiflorum lindl leaves</i>	-	Al	1 M HCl	WL, polarization, EIS, SEM	-	Langmuir
[81]	<i>Dendrocalamus brandisii leaves</i>	-	Al	0.5–3 M HCl & H <sub>3</sub> PO <sub>4</sub>	WL, polarization, EIS, SEM	91.30, 47.1	Langmuir
[82]	<i>Morinda tinctoria leaves</i>	-	Al	0.5 M HCl	WL, additives KCl, KBr, KI	-	Langmuir
[83]	<i>Thymus algeriensis roots &amp; leaves</i>	-	Al 2024	1 M HCl	WL, 298–338 K, gasometric, EIS	78.7	Langmuir
[84]	<i>Coriander seeds</i>	-	Al 99.20%	1 M HCl	WL, PDP, EIS, GC-MS	82.49	Langmuir
[85]	<i>Shatavari (Asparagus racemosus)</i>	-	Al 99.60%	1 M HCl	WL, 288–303 K, SEM, quantum chemical analysis	80.54	Langmuir

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Ref.	Inhibitors	Extract	Metal	Solutions	Methods	Inhibition efficiency (%)	Adsorption isotherms
[86]	<i>Phoenix dactylifera</i> leaves, male & female	-	Al commercial	1 M HCl	WL, 313–333 K	88.70 male, 95.16 female	Langmuir, Freundlich, Frumkin, Temkin, El-Awady, Flory-Huggins
[87]	<i>Cassia alata</i> leaves	Alcohol, 48 h	Al	1 M HCl	WL, 303–353 K, FTIR, UV, EDX	87.67	Langmuir
[88]	<i>Azadirachta indica</i> fruit	Ethanol, Soxhlet, 24 h	Al 98%	0.5 N HCl	WL, 303–353 K, FTIR	92.37	Langmuir
[89]	<i>Tussilago farfara</i>	Methanol (70%), 48 h	Al 99.98%	2 M HCl	Gassometry, WL, PDP, EIS, EFM	94.2	Langmuir
[90]	<i>Juglans regia</i>	Methanol (70%), 48 h	Al 99.98%	2 M HCl	Gassometry, WL, PDP, EIS, EFM	98.7	Langmuir
[91]	<i>Trigonella foenum gracenum</i> seed	Ethanol	Al AA6063	0.5 M HCl	WL, additives Zn <sup>2+</sup> > Br <sup>-</sup> > Cl <sup>-</sup> > I <sup>-</sup>	83.3	-
[92]	<i>Tecoma</i>	Non aqueous solvent	Al	1 M H <sub>2</sub> SO <sub>4</sub>	WL, PDP, EIS, EFM	90.20	Langmuir
[93]	<i>Bassia muricata</i>	Ethanol 4 days	Al 99.55%	1 M H <sub>2</sub> SO <sub>4</sub>	WL, 298–318 K, PDP, EIS, EFMc	90.0	Temkin
[94]	<i>Ficus carica</i> leaves	Methanol	Al alloy	0.5 M HCl	WL, 303–333 K	91.34	Langmuir, Frumkin
[95]	<i>Ziziphus mauritiana</i> fruit	Ethanol, Soxhlet 24 h	Al	0.5 M HCl	WL	76.80	Langmuir
[96]	<i>Green coffee bean</i>	Methanol (99.8%), 48 h	Al	Acid rain	PDP, 303–333 K	98.08	Langmuir
[97]	<i>Breadfruit peels</i>	Acetone (50%)	Al	0.5 M H <sub>2</sub> SO <sub>4</sub>	WL, 303–333 K	85.3	Langmuir
[98]	<i>Ziziphus jujube</i> leaves	Methanol (80%), 5 h	Al 95.9%	1 M HCl	WL, SEM	91.26	Langmuir

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Ref.	Inhibitors	Extract	Metal	Solutions	Methods	Inhibition efficiency (%)	Adsorption isotherms
[99]	<i>Black mulberry fruits (Morus nigra)</i>	Ethanol, 6 h	Al 99.99%	2 M HCl	WL, PDP, hydrogen evolution	93.44% 98%	Langmuir
[100]	<i>Veronia amygdalina leaves</i>	Ethanol, DW, HCl	Al	1 M HCl	WL, 303–333 K	99.10%, 94.3%, 92.0%	Langmuir, Flory Huggins
[101]	<i>Ocimum gratissimum leaves</i>	DW, ethanol, 1 M HCl	Al AA1066	1 M HCl	WL	DW > ethanol > 1 M HCl	Langmuir, Flory Huggins
[102]	<i>Withania somnifer leaves &amp; root</i>	Ethanol, Soxhlet	Al commercial	0.5, 1, and 2 M HCl	WL, 303–333 K	98.53	Langmuir
[103]	<i>Basil</i>	Ethanol, Soxhlet	Al 98.5%	0.5–3 M HCl	WL	97.09	Langmuir
[104]	<i>Coconut coir dust</i>	Acetone, 48 h	Al 98.60%	1 M HCl	WL, hydrogen evolution, FTIR, 303–333 K	80.0	Langmuir
[105]	<i>Cumin seeds</i>	Methanol, 24 h	Al	1 M HCl	WL, 308–338 K, polarization, EIS	99.6	Langmuir
[106]	<i>Albizia lebeck seed</i>	Alcohol, 48 h	Al	1 M HCl	FTIR, WL, 303–333 K	92.31	Langmuir
[107]	<i>Portulaca oleracea leaves</i>	Ethanol, 48 h	Al commercial	2 M H <sub>2</sub> SO <sub>4</sub>	WL, 305–315 K	45.16	Langmuir, Freundlich, Temkin
[108]	<i>Manihot esculentum leaves</i>	Ethanol, 48 h	Al commercial	2 M H <sub>2</sub> SO <sub>4</sub>	WL, 305–315 K	50.0	Freundlich, El-Awady
[109]	<i>Manihot esculentum root peel</i>	Ethanol, 48 h	Al commercial	2 M H <sub>2</sub> SO <sub>4</sub>	WL, 305–315 K	43.33	Langmuir, Freundlich, Temkin
[110]	<i>Phoenix dactylifera plant</i>	Petroleum, ether and methanol	Al 99.55% & 92.48%	0.5 M HCl	PDP, EIS, EFM, 293–333 K	89.1 & 91.8	Langmuir
[111]	<i>Garlic (allium) skin</i>	Acetone	Al 97.58%	0.5 M HCl	WL, 303–323 K	95.0	Langmuir, Temkin
[112]	<i>Murraya Koenigii leaves</i>	Ethanol	Al alloy 6063	0.5 M HCl	WL, 303–333 K	96.43	Langmuir

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Ref.	Inhibitors	Extract	Metal	Solutions	Methods	Inhibition efficiency (%)	Adsorption isotherms
[113]	<i>Sorghum bicolor</i> leaves	Ethanol, 48 h	Al 99.8%	2 M H <sub>2</sub> SO <sub>4</sub>	WL, 305–315 K	50.0	Langmuir, Freundlich, Temkin, El-Awady
[114]	<i>Sapium ellipticum</i> leaves	Ethanol, 48 h	Al 97.0%	1–2 M HCl	WL, 303–333 K, PDP, SEM	96.73	Langmuir
[115]	<i>Azadirachta indica</i> leaves	Ethanol, 7 days	Al 98.50%	0.5–2 M HCl	WL, 303–333 K	54.60	Langmuir
[116]	<i>Kola nitida</i> seeds	Ethanol, 48 h	Al AA3003	0.1 M HCl	WL, PDP, EIS	85.0	Langmuir
[117]	<i>Nicotiana tabacum</i> leaves	Ethanol, 48 h	Al AA3003	0.1 M HCl	WL, PDP, EIS, EFM, SEM	84.80	Langmuir
[118]	<i>pawpaw (Carica papaya)</i> leaves	Ethanol, 48 h	Al 99.50%	1 M HCl	WL, 303–333 K, PDP, FT-IR	81.99	Langmuir, Frumkin, Temkin, Flory-Huggins
[119]	<i>Jatropha curcas</i> leaves	Ethanol (96%), 72 h	Al AA60	1 M HCl	WL, 303–333 K	76.49	Freundlich, Temkin, El-Awady,
[120]	<i>Dry arecanut seed</i>	Hexane, 5 h	Al A-63400	0.5 M HCl	WL, 303–323 K, PDP, EIS, SEM, AFM	83.33	Langmuir
[121]	<i>Peganum harmala</i> plant	Methanol, 2 h	Al Alloy 6063	1 M HCl	WL, 298–313 K, PDP	89.0	Langmuir
[122]	<i>Persea Americana</i> leaves ( <i>Avocado pear</i> )	Ethanol 48 h	Al	1 M H <sub>2</sub> SO <sub>4</sub>	WL, 313–333 K	78.90	Langmuir, Temkin
[123]	<i>Phyllanthus amarus</i> leaves	Ethanol 48 h	Al	1 M HCl	WL, 303–333 K, PDP, quantum chemical study, SEM	93.93	Langmuir, Freundlich
[124]	<i>Acacia senegalensis</i> stem	Ethanol, 48 h	Al	0.5 M H <sub>2</sub> SO <sub>4</sub>	WL, 313–343 K, PDP, SEM	92.66	Langmuir
[125]	<i>Cordia dichomota</i> seeds	Ethanol 24 h	Al AA6063	0.5 M HCl	WL, 293–353 K, PDP, EIS, SEM, FTIR	90.63	Langmuir, El-Awady

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Ref.	Inhibitors	Extract	Metal	Solutions	Methods	Inhibition efficiency (%)	Adsorption isotherms
[126]	<i>Hemerocallis fulva</i>	-	Al	1 M H <sub>2</sub> SO <sub>4</sub>	WL, 303–333 K, PDP, EIS, AFM, SEM, FTIR	89.0	Langmuir
[127]	<i>Euphorbia neriifolia</i> <i>linn</i>	Ethanol, 15–20 h	Al commercial	1–3 M HNO <sub>3</sub>	WL, thermometric	92.62	Langmuir
[128]	<i>Euphorbia neriifolia</i> <i>linn</i>	Ethanol, 15–20 h	Al commercial	1–3 M HCl	WL, thermometric	94.92	Langmuir
[129]	<i>Fennel seeds (F. Vulgare)</i>	Methanol	Al 99.54%	0.75–1.25 M HCl	WL, 313–333 K	92.01	Langmuir
[130]	<i>Strichnos spinosa</i> <i>leaves</i>	Ethanol (95%), 2 days	Al 98.70%	0.3 M HCl	WL, 303–323 K, PDP, SEM, Ft-IR	88.48	Langmuir, Freundlich
[131]	<i>Capparis decidua</i> <i>fruits, stem &amp; roots</i>	Ethanol, 48 h	Al 98.02%	1–3 M HCl, 0.5–2 M H <sub>2</sub> SO <sub>4</sub>	WL, 303–323 K	98.73, 94.02, 94.92 for HCl and 62.92, 69.54 80.22, for H <sub>2</sub> SO <sub>4</sub>	Langmuir
[132]	<i>Treculia African</i> <i>leaves</i>	Ethanol, 3 days RT	Al AA1066	1 M HCl	WL, 303–333 K	74.17	Freundlich, El-Awady
[133]	<i>Dryopteris cochleate</i> <i>leaves</i>	Methanol, 3 h	Al 98.5%	1 M H <sub>2</sub> SO <sub>4</sub>	WL, 298–338 K, PDP, EIS, SEM, FT-IR	84.62	Freundlich
[134]	<i>Allamanda</i> <i>cathartica leaves</i>	Methanol, 24 h	Al AA8011	1 M HCl	WL, 303–323 K	85.0	Freundlich
[135]	<i>Chrysophyllum</i> <i>albidum fruit</i>	Ethanol 95%	Al 99.0%	1.5 M H <sub>2</sub> SO <sub>4</sub>	WL, 303–333 K	40.52	Temkin
[136]	<i>Prosopis laevigata</i> <i>leaves</i>	Methanol, 24 h	Al	0.5 M H <sub>2</sub> SO <sub>4</sub>	WL, 293–333 K, PDP, EIS	93.53	Frumkin, Temkin,
[137]	<i>Lawsonia inermis</i> <i>seed</i>	Alcohol, 48 h	Al	0.5 M HCl	WL, 303–333 K, EDAX, FTIR, UV	84.52	Temkin
[138]	<i>Anogeissus</i> <i>leiocarpus leaves</i>	Ethanol, 1 week	Al 98.70%	0.2–0.8 M HCl	WL, 308–338 K, additives KCl, KBr, KI	95.18 I > Br > Cl	-
[139]	<i>Gongronema</i> <i>latifolium</i>	Ethanol	Al 98.98%	0.5–2 M HCl	WL, 303–333 K	74.14	-

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Ref.	Inhibitors	Extract	Metal	Solutions	Methods	Inhibition efficiency (%)	Adsorption isotherms
[140]	<i>Polygonatummoda ratum leaves</i>	Methanol, 24 h	Al 99.89%	1 M HCl	WL, 303–333 K, PDP, EDX, SEM	94.70	-
[141]	<i>Talinum triangular leaves &amp; Musa sapientum peel</i>	Ethanol, 48 h	Al Alloy ZA-27	1–1.5 M HCl	WL, 303–333 K	62.30 & 63.27	-
[142]	<i>Garlic</i>	Ethanol	Al	0.05 M H <sub>3</sub> PO <sub>4</sub>	WL, 303–333 K, PDP, EIS,	90.0	-
[143]	<i>Solanum xanthocarpum stem &amp; leaves</i>	Ethanol	Al commercial	2 M HCl	WL, gasometric	83.85 stem, 94.53 leaves	-
[144]	<i>Acanthocereus tetragonus</i>	Aqueous	Al	1 M HCl	EIS, polarization	7.5	-

The category of extraction solvent and the separation process could have an important influence on the yield of materials extracted from plant materials. Each extraction method has distinct operating parameters that influence the content and antioxidant action of the extract and is essential to be optimized. The solvent to temperature, feed ratio, extraction time, number of repetitive sample extractions, and the ideal of extraction solvents are primary factors monitoring extraction reactions. Solubility is extremely impacted by the temperature and extraction time. At the greater extraction rate, surface tension, viscosity, and temperature of solvents decrease, which motivates rates of the mass transfer [145]. Material pretreatment, which influences the particle size, distribution, sample matrix, and moisture content is another factor that influences the extraction rate [146].

The majority of the utilized solvents were documented as being of environmental worry. These worries arise in 3 parts: (1) the solvent's source and production; (2) its properties in usage, counting accidental discharge; (3) and disposal. There is widespread agreement among proponents of solvent usage in the literature that a solvent or group of solvents must be considered characteristically green. Solvents and their groups that were recommended as green solvents included water, ionic liquids, supercritical fluids, gas extended liquids, and solvents derived from biomass [147]. Biomass is an exceptional renewable substitute resource for manufacturing bio-solvent alcohol. Most of the researchers used methanol and ethanol as a solvent for the extraction while some used the acid solution itself as a solvent, and used as a corrosion inhibitor and noted extraordinary inhibition efficiency, which can be shown in column III of Table 1. Because alcohol is well recognized to be safer for human use and it is widely used for the “anthocyanin-rich phenolic” compounds extraction and also applied to obtain flavonoids from plant tissues.

Adsorption is the 1<sup>st</sup> stage of developing a corrosion-protective coat or film on a metallic surface in active locations in the existence of aggressive media. Many variables influence the inhibitor adsorption on the “metallic surface” and its isolation such as adsorption mode, electronic and chemical features of the inhibitor, kind of electrolyte applied, temperature, steric effect, and the type and surface charge of the metals [148]. An adsorption isotherm is a useful tool for explaining the corrosion inhibition process. Adsorption on metal surfaces is frequently categorized as physisorptions or chemisorptions, based on the interaction strength between the surface as well as the absorbed molecule.

The connection between inhibition effectiveness and the majority of inhibitor content at a constant temperature, recognized as isotherm [149], gives information about the adsorption process.

The metal corrosion inhibition by extract were accredited to their adsorption on to aluminum metal alloy surface. This may be generally established from the experimental data fitness to several adsorption isotherms but most fitted is as Langmuir [36–53,59–70,76–131]. Temkin [42,48,62,66,70–72,79,86,93,107,109,111,113,118,119,122,135–137], Frumkin [76,86,94,118,136], Freundlich [48,52,54–55,70,73,86,107–109,113,119,123,130,132–134], Florry Hugginsn [49,86,100–101,118] and El-Awardy [86,108,113,119,125,132] isotherms are frequently used by the researcher. The general form of above all isotherms is presented as below [150]:

$$f(\theta, x) \exp(-2\alpha\theta) = KC. \quad (10)$$

Here,  $f(\theta, x)$  denotes a configurationally factor,  $\theta$  indicates the surface coverage area,  $x$  represents the size ratio,  $K$  represents the equilibrium constant,  $\alpha$  denotes the parameter of molecular interaction, and  $C$  signifies the inhibitor concentration, based on the physical paradigm and assumptions behind the isotherm derivative [151].

Table 1 of column VIII displays the assessments of “Langmuir isotherm” with other models like Frumkin, Temkin, Freundlich, Florry Hugginsn, and El-Award. Langmuir isotherm typical adopt that the process of the adsorption happens on definite homogeneous sites on the metal surface and it is utilized to countless outcomes in numerous monolayer adsorption processes [152]. The following equation was applied to compute the Gibbs free energy of adsorption ( $\Delta G^0_{ads}$ ).

$$\text{Log } P_1/P_2 = E_a/2.303RT \left[ 1/T_1 - 1/T_2 \right], \quad (11)$$

where  $C$  is the inhibitor concentration and  $\text{Log } B = -1.74 - \Delta G^0_{ads}/2.303RT$ . The  $\Delta G^0_{ads}$  values of all tested green inhibitors were found to be negative and evidence that the inhibitor concentration rises the  $\Delta G^0_{ads}$  values decrease in order, showing that the most effective inhibitor displays more negative  $\Delta G^0_{ads}$  value. This indicates that they are well adsorbed on the metal surface. Usually, the  $\Delta G^0_{ads}$  values are less negative as compared to  $-20 \text{ kJ}\cdot\text{mol}^{-1}$  represents physical adsorption whereas those are more negative as compared to  $-40 \text{ kJ}\cdot\text{mol}^{-1}$  signifies chemical adsorption [153,154]. In most of the tested green inhibitors attached adsorption the inhibition effectiveness with temperature rise specifies physical adsorption.

The following Arrhenius Equation was applied to compute the  $E_a$  (“Activation Energy”) (12). Here  $P_1$  and  $P_2$  represent the corrosion rate at temperatures  $T_1$  and  $T_2$  respectively.

$$\text{Log } P_1/P_2 = E_a/2.303RT \left[ 1/T_1 - 1/T_2 \right]. \quad (12)$$

In all the tested green inhibitors, it is observed that acid comprising inhibitors’ mean values of  $E_a$  are observed to be greater than the uninhibited system. The greater  $E_a$  values in the existence of inhibitors evaluated to the “blank coupled” with a drop in the inhibition effectiveness with temperature rise may be interpreted as assign of physical inhibitor adsorption on the metal surface [155]. Greater  $E_a$  values in the existence of extract may also be connected with the rise in double-layer thickness that improves the  $E_a$  of the corrosion process [156]. In all the cases it is observed that the values derived from the Arrhenius plot and the equation are found to be the same. The adsorption enthalpy and the



adsorption entropy were computed by the following Eqs (13) and (14).

$$\Delta H_{ads}^0 = E_a - RT, \quad (13)$$

$$\Delta S_{ads}^0 = (\Delta H_{ads}^0 - \Delta G_{ads}^0)/T, \quad (14)$$

the values of  $\Delta H_{ads}^0$  are positive, signifying the endothermic reaction nature signifying that an increase in temperature promotes the corrosion process [157]. And the  $\Delta S_{ads}^0$  values are also found in all tested extracts are positive, verifying that the “corrosion process” is entropically favorable [158].

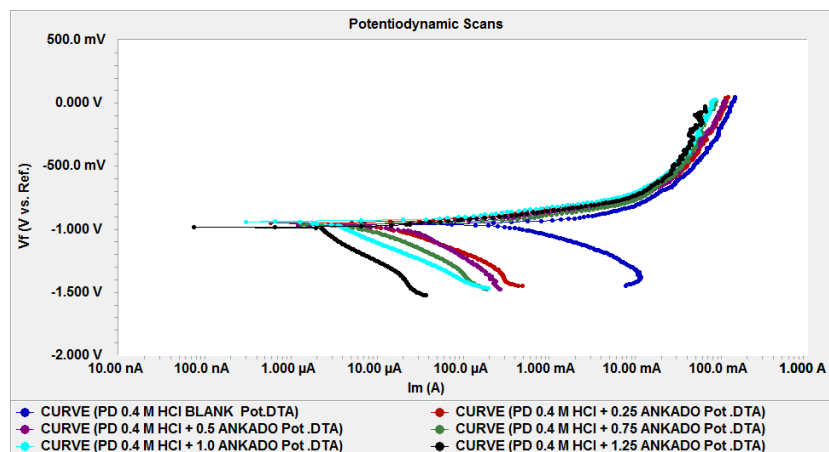
Generally, the inhibition efficacy of this extracted inhibitor improved with the rising inhibitor level but reduced with rising temperature. In the case of *Cassia alata* leaves the inhibition efficacy value is raised with the rise in temperature [87]. Therefore, the inhibitor efficacies are temperature dependent and it is being chemically adsorbed at higher temperatures. This is mainly owing to the molecule’s active adsorption on the surface of the metal being greater than the desorption process. Green inhibitors have characteristics that are comparable to non-green inhibitors. The majority of the eco-friendly inhibitors adsorb on a metal surface using chemical and physical adsorption at room temperature. On extensive exposure to the eco-friendly inhibitor in the direction of the corrosive environment, the inhibitor increases or decreases its efficiency during the progression of corrosion inhibition. The progression of the influence of augmented time on the inhibition efficacy lends information about the effectiveness of the inhibitor decreases upon the inhibitor molecules on the metal surface occurs predominantly with a physical interface.

The polarization measurements suggested that these extracted ark from the different parts from the plants acted as mixed type inhibitors [36–40,44,45,50,51,53–55,59,69,75–79,81,89,90,92,93,99,105,110,114,118,120,121,123,125,126,130,133,141,142]. Tafel polarization graph shows all tested extract inhibitors are observed decrease in the corrosion rate, which could be elucidated by the changing of cathodic curves to lower current densities values. Except anodic response of corrosion process is slightly with papaya peel extract [55].

Polarization data showed that the *curry* leaves extract operated as an anodic type inhibitor at lower contents of the inhibitor and as a mixed type at greater inhibitor contents [61]. The displacement in corrosion potential is higher than  $\pm 85$  mV with respect to blank corrosion potential, then the inhibitor could be deemed particularly as an anodic or cathodic type. In the current studies, the greatest positive displacement for aluminum in sulfuric acid was more than 85 mV. This finding suggests that inhibitor molecule elements may operate as anodic types, bringing the anodic process under control [47]. The curves of potentiodynamic polarization, clearly examine that the values of  $E_{corr}$  moved to more negative potential with the rise in green coffee bean concentration [96], few scientists observed cathodic type inhibitors [55,65,66,80,81,87,117].

The Tafel polarization graphs of aluminum in hydrochloric acid solution, in the absence and presence of diverse concentration of *Calotropis gigantean* leaves extract, are presented in Figure 2. The values of corrosion current densities in the presence ( $2.76 \mu\text{A}/\text{cm}^2$ ) and absence ( $203.0 \mu\text{A}/\text{cm}^2$ ) of inhibitor were obtained from the graph, the maximum inhibition efficiency (98%) was observed at 1.25% inhibitor concentration. Addition of the *Calotropis gigantea* leaf extract to acid solution affected both the cathodic and anodic parts of the curves. *Calotropis gigantea* extract, influenced both the anodic dissolution of aluminum and the generated hydrogen gas at the cathode indicating that the extract behaved as mixed-type inhibitor. The decrease in the observed limiting current with increasing

*Calotropis gigantea* concentration indicated that the anodic process is controlled by diffusion. From the polarization figure it was noted that the curves were shifted towards the lower current density region and  $\beta_a$  and  $\beta_c$  values did not showed any significant change. While the corrosion potential with *Calotropis gigantea* was slightly negative  $-986$  mV, then the without inhibitor observed  $-958$  mV [54].



**Figure 2.** Polarization curve for *Calotropis gigantea* leaves extract in HCl.

EIS is the best method to provide data about the interface's capacitive and resistive behavior as well as assess the influence of extracted compounds on aluminum in acid media. EIS is noted and exhibited by the "Nyquist plot" and, contains two constants; an inductive time constant at lower rates and a capacitive time constant at higher rates. In the EIS a small diameter is noticed in the uninhibited system while the content of inhibitors rises, a diameter becomes greater because of rising resistance. The time constant of capacitive initiates because of the charge transfer mechanism created on moreover the electron conduction via the direct electron transfer or surface film on the surface of the metal. The 1<sup>st</sup> time constant is described in terms of "electric double-layer" and charge transfer due to the dielectric characteristics of the surface layer [159]. However, due to the adsorbed charged intermediates, an inductive time constant develops [160]. However, many researchers supposed that relaxation "adsorption intermediates" on the electrode surface contain Cl [161], oxygen [162], or inhibitor types [163]. Inductive behaviour could also be seen in the pitted active state, which may be ascribed to salt layer property modulation, surface area modulation, or oxide layer surface redissolution [164], examined extract inhibitors explain that aluminum continues to dissolve through the "charge transfer" process on the absorbed inhibitor aluminum surface [165]. The polarization resistance may be measured from the Eq (6). Both  $R_p$  and  $R_{ct}$  values rise considerably with the addition of tested extract, which elucidates about slower corrosion rate of the electrode process in the existence of inhibitors. The Value of  $R_p$  was raised, and there was a drop in the  $C_{dl}$  values. Therefore, the efficient corrosion resistance was noted to be allied with the higher  $R_p$  value and the lower  $C_{dl}$  value. The  $C_{dl}$  is described as an "electrical capacitor" when deemed between the surface metal charge and the solution. In most of the cases observed in the bode spectrum, 2-time constants are apparent, such as a middle frequency and low-frequency time constant. The middle frequency time constant accredited to the "capacitive" behavior of the air formed layer covering the microscopic aluminum surface whereas the low-frequency connected to the inductive behaviour escorted with the impedance decomposition with frequency decreases consistently to the adsorbed species relaxation process within the oxide layer

covering the electrode surface [111]. The inhibitor particle adsorbs on the surface of the metal, reducing its electrical ability by repositioning water molecules as well as adsorbed ions on the surface, as shown by the production of a protective coating on the electrode surface [166].

SEM method provides a pictographic depiction of the metal surface. To comprehend the type of the surface layer in the inhibitor's absences and the presence and extent of the corrosion of aluminum products and their alloy, the SEM micrographs of the surface are studied [167]. The results indicate that the surface is enclosed by a thin film of inhibitors which efficiently controls the aluminum metal dissolution by corrosion agents. The above outcomes are consistent with the explanation made by [43,53,55,62,65,70,75–77,79–81,85,98,114,117,123,125,126,130,133].

There are few researchers who used additives (KI, KBr, KCl) in the inhibition process. The “synergistic parameter” (S) was assessed using the connection provided by Armaki and Hackerman, and described elsewhere [168].

$$S = \frac{1 - I_{A+B}}{1 - I'_{A+B}}, \quad (15)$$

$$S = \{1 - I_A - I_B + I_A I_B\} / (1 - I'_{A+B}), \quad (16)$$

where,  $I_{A+B} = I_A + I_B$ ;  $I_A$  and  $I_B$  indicate the inhibition efficacies of ion-additives and green inhibitors when used alone and  $I'_{A+B}$  = the “inhibition efficiency” of co-employment of 2 inhibitors. The following conclusions may be derived from the S value obtained: if S is greater than 1: the two inhibitors function synergistically; if S is less than 1: the 2 inhibitors act antagonistic; and if S = 1: molecules that operate as inhibitors don't interact with one other. The values of S for (green inhibitors + ion-additives) were assessed and observed to be higher than unity, thereby 2 inhibitors act synergistically [60,68,82,91,138]. The process of synergism could be conceptualized as follows: the active elements of extracts are first adsorbed onto the metal surface where the ion additives were already adsorbed through coulombic attraction. This inhibits corrosion by stabilizing the deposited ions and raising the surface coverage of the metal surface previously covered. When aluminum-ion surface bonds were formed during extraction, their adsorption reduced aluminum's positive charge and allowed the extract's active constituents to be more easily absorbed [169].

#### 4. Conclusions

This review paper summarizes research on aluminum corrosion and its alloys in various acid solutions utilizing a range of natural chemicals that have been published over the last several decades. Plant extracts were by far the utmost examined natural occurring products. A range of solvents was utilized for the extraction, mainly seeds, stems, and leaves of the respective plants. Usually, green corrosion inhibitors are outstanding inhibitors under a diversity of corrosive environments for the aluminum alloy. The non-poisonous and biodegradability are the most important advantages of these eco-friendly inhibitors. Although, they have lots of performance boundaries. However, many articles are witnessing the “green inhibitors” as potent applicants against corrosion in various environments; more research attempts are required to employ the green inhibitors extensively at an industrial level.

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## Conflict of interest

The authors have no conflicts of interest to declare.

## References

1. Shaker RR (2015) The spatial distribution of development in Europe and its underlying sustainability correlations. *App Geogr* 63: 304–314. <https://doi.org/10.1016/j.apgeog.2015.07.009>
2. Shehata OS, Korshed LA, Adel Attia (2018) Green corrosion inhibitors, past, present and future, In: Aliofkhazraei M (Ed.), *Corrosion inhibitors, principles and recent applications*, London: IntechOpen. <https://doi.org/10.5772/intechopen.72753>
3. Revie RW, Uhlig HH (2008) In: *Corrosion and corrosion control: An introduction to corrosion science and engineering*, 4 Eds., New Jersey: John Wiley & Sons.
4. Hurlen T, Liam H, Odegard OS, et al. (1984) Corrosion and passive behaviour of aluminium in weakly acid solution. *Electrochem Acta* 29: 579. [https://doi.org/10.1016/0013-4686\(84\)87113-3](https://doi.org/10.1016/0013-4686(84)87113-3)
5. Rengamani S, Muralidharan S, Kulandainathan MA, et al. (2005) Inhibiting and accelerating effects of aminophenols on the corrosion and permeation of hydrogen through mild steel in acidic solutions. *J Appl Electrochem* 24: 355–360. <https://doi.org/10.1007/BF00242066>
6. Shehata OS, Korshed LA, Attia A (2018) Green corrosion inhibitors, past, present, and future, In: Aliofkhazraei M (Ed.), *Corrosion inhibitors principles and recent application*, London: IntechOpen, 121–122. <http://doi.org/10.5772/intechopen.72753>
7. Desai PS, Kapopara SM (2009) Inhibiting effect of anisidines on corrosion of aluminium in hydrochloric acid. *Indian J Chem Technol* 16: 486–491.
8. Desai PS, Vashi RT (2009) Performance of phenylthiourea as corrosion inhibitor for aluminum in trichloroacetic acid. *J Indian Chem Soc* 86: 547–550.
9. Desai PS, Vashi RT (2010) Efficiency of xylenol orange as corrosion inhibitor for aluminium in trichloroacetic acid. *Indian J Chem Technol* 17: 50–55.
10. Bentiss F, Traisnel M, Chaibi N, et al. (2002) 2,5-Bis(n-methoxyphenyl)-1,3,4-oxadiazoles used as corrosion inhibitors in acidic media: Correlation between inhibition efficiency and chemical structure. *Corrs Sci* 44: 2271–2789. [https://doi.org/10.1016/S0010-938X\(02\)00037-9](https://doi.org/10.1016/S0010-938X(02)00037-9)
11. Li XM, Tang LB (2005) Synergistic inhibition between OP and NaCl on the corrosion of cold-rolled steel in phosphoric acid. *Mater Chem Phys* 90: 286–297.
12. Desai PS, Kapopara SM (2014) Inhibitory action of xylenol orange on aluminum corrosion in hydrochloric acid solution. *Indian J Chem Technol* 21: 139–145
13. Desai PS, Vashi RT (2011) Inhibitive efficiency of sulphathiazole for aluminum corrosion in trichloroacetic acid. *Anti-Corros Methods M* 58: 70–75. <https://doi.org/10.1108/00035591111110714>

14. Aljourani J, Raeissi K, Golozar MA (2009) Benzimidazole and its derivatives as corrosion inhibitors for mild steel in 1M HCl solution. *Corros Sci* 51: 1836–1843. <https://doi.org/10.1016/j.corsci.2009.05.011>
15. Vermeirssen ELM, Dietschweiler C, Werner I, et al. (2017) Corrosion protection products as a source of bishphenol A and toxicity to the aquatic environment. *Water Res* 123: 586–593.
16. Raja PB, Ghoreishiamiri S, Ismail M (2015) Natural corrosion inhibitors for steel reinforcement in concrete—a review. *Sufr Rev Lett* 22: 1550040.
17. Bereket G, Yurt A (2001) The inhibition effect of amino acid and hydroxy carboxylic acid on pitting corrosion of aluminum alloy 7075. *Corros Sci* 43: 1179–1195. [https://doi.org/10.1016/S0010-938X\(00\)00135-9](https://doi.org/10.1016/S0010-938X(00)00135-9)
18. Rani BEA, Basu BBJ (2012) Green inhibitors for corrosion protection of metals and alloys: An overview. *Int J Corros* 2012: 380217. <https://doi.org/10.1155/2012/380217>
19. Radojicic I, Berkovic K, Kovac S, et al. (2008) Natural honey and black radish juice as tin corrosion inhibitors. *Corros Sci* 50: 1498–1504
20. Sanyal B (1981) Organic compound as corrosion inhibitors in different environment—A review. *Prog Org Coat* 9: 165–236. [https://doi.org/10.1016/0033-0655\(81\)80009-X](https://doi.org/10.1016/0033-0655(81)80009-X)
21. Lai X, Hu JF, Ruan T, et al. (2021) Chitosan derivative corrosion inhibitor for aluminum alloy in sodium chloride solution: A green organic/inorganic hybrid. *Carbohydr Polym* 265: 118074. <https://doi.org/10.1016/j.carbpol.2021.118074>
22. UmorenSA, AlAhmaryAA, Gasem ZM, et al. (2018) Evaluation of chitosan and carboxymethyl cellulose as ecofriendly corrosion inhibitors for steel. *Int J Biol Macromol* 117: 1017–1028. <https://doi.org/10.1016/j.ijbiomac.2018.06.014>
23. Gupta NK, Joshi PG, Vandana Srivastava V, et al. (2018) Chitosan: A macromolecule as green corrosion inhibitor for mild steel in sulfamic acid useful for sugar industry. *Int J Biol Macromol* 106: 704–711. <https://doi.org/10.1016/j.ijbiomac.2017.08.064>.
24. Liu HL, Zhu ZM, Hu JF, et al. (2022) Inhibition of Q235 corrosion in sodium chloride solution by chitosan derivative and its synergistic effect with ZnO. *Carbohydr Polym* 296: 119936. <https://doi.org/10.1016/j.carbpol.2022.119936>
25. Marzorati S, Verotta L, Trasatti SP (2019) Green corrosion inhibitors from natural sources and biomass wastes. *Molecules* 24: 48. <https://doi.org/10.3390/molecules24010048>
26. Zou Y, Wang J, Zheng YY (2011) Electrochemical techniques for determining corrosion rate of rusted steel in seawater. *Corros Sci* 53: 208–216. <https://doi.org/10.1016/j.corsci.2010.09.011>
27. Law DW, Millard SG, Bungey JH (2000) Linear polarization resistance measurements using a potentiostatically controlled guard ring. *NDT E Int* 33: 15–21. [https://doi.org/10.1016/S0963-8695\(99\)00015-8](https://doi.org/10.1016/S0963-8695(99)00015-8)
28. Andrade C, Alonso C (1996) Corrosion rate monitoring in the laboratory and on-site. *Constr Build Mater* 10: 315–328. [https://doi.org/10.1016/0950-0618\(95\)00044-5](https://doi.org/10.1016/0950-0618(95)00044-5)
29. Sadowski L (2010) New non-destructive method for linear polarisation resistance corrosion rate measurement. *Arch Civ Mech Eng* 10: 109–116. [https://doi.org/10.1016/S1644-9665\(12\)60053-3](https://doi.org/10.1016/S1644-9665(12)60053-3)
30. Orazem ME, Tribollet B (2008) In: *Electrochemical impedance spectroscopy*, New Jersey: John Wiley & Sons. <https://doi.org/10.1002/9780470381588.scard>
31. GAMRY (2018) EIS-Electrochemical Impedance Techniques. Available from: <https://www.gamry.com/application-notes/EIS/potentiostatic-eis-tutorial/>.

32. Yadav AP, Nishikata A, Tsuru T (2004) Electrochemical impedance study on galvanized steel corrosion under cyclic wet–dry conditions—influence of time of wetness. *Corros Sci* 46: 169–181. [https://doi.org/10.1016/S0010-938X\(03\)00130-6](https://doi.org/10.1016/S0010-938X(03)00130-6)
33. Galal A, Atta NF, Al-Hassan MHS (2005) Effect of some thiophene derivatives on the electrochemical behavior of AISI 316 austenitic stainless steel in acidic solutions containing chloride ions: I. Molecular structure and inhibition efficiency relationship. *Mater Chem Phys* 89: 38–48. <https://doi.org/10.1016/j.matchemphys.2004.08.019>
34. Quarishi MA, Rawat AJ (2002) Inhibition of mild steel corrosion by some macrocyclic compounds in hot and concentrated hydrochloric acid. *Mater Chem Phys* 73: 118–122. <http://doi.org/10.1016/S0254-0584%2801%2900374-1>
35. Uma K, Rajapriya V, Rekha S (2016) The effect of inhibitor on the corrosion of aluminium in acidic solutions. *SOJ Mater Sci Eng* 4: 1–6. <http://doi.org/10.15226/sojmse.2016.00140>
36. Raghavendra N, Ishwara Bhat J (2016) Green approach to inhibition of corrosion of aluminum in 0.5 M HCl medium by tender arecanut seed extract: Insight from gravimetric and electrochemical studies. *Res Chem Intermed* 42: 6351–6372. <https://doi.org/10.1007/s11164-016-2467-1>
37. Raghavendra N, Bhat JI (2016) Natural products for material protection: An interesting and efficacious anticorrosive property of dry arecanut seed extract at electrode (aluminum)–electrolyte (hydrochloric acid) interface. *J Bio Tribo Corros* 2: 21. <https://doi.org/10.1007/s40735-016-0051-2>
38. Ladha DG, Wadhvani PM, Kumar S, et al. (2015) Evaluation of corrosion inhibitive properties of *Trigonella foenum-graecum* for pure Aluminium in hydrochloric acid. *J Mater Environ Sci* 6: 1200–1209.
39. Al-Rudaini KAK, Ai-Saadie KAS (2021) Study the Corrosion behavior of AA7051 Aluminum alloy at different temperatures and inhibitor concentration in Acidic medium. *Res J Pharm Technol* 14: 4977–4982.
40. Prabhu D, Rao P (2013) *Coriandrum sativum* L.—A novel green inhibitor for the corrosion inhibition of aluminium in 1.0 M phosphoric acid solution. *J Environ Chem Eng* 1: 676–683. <https://doi.org/10.1016/j.jece.2013.07.004>
41. Babatunde AI, Ogundele O, Oyelola OT, et al. (2012) The inhibitive effect of *Irvingia gabonensis* extract on the corrosion of aluminium in 1M HCl solution. *Adv Appl Sci Res* 3: 3944–3949.
42. Emran KM, Ahmed NM, Torjoman BA, et al. (2014) Cantaloupe extracts as eco friendly corrosion inhibitors for aluminum in acidic and alkaline solutions. *J Mater Environ Sci* 5: 1940–1950
43. Al-Haj-Ali AM, Jarrah NA, Mu'azu ND, et al. (2014) Thermodynamics and kinetics of inhibition of aluminum in hydrochloric acid by date palm leaf extract. *J Appl Sci Environ Manage* 18: 543–551.
44. Pushpanjali M, Rao SA, Padmalatha (2014) *Carica papaya* seeds-green inhibitor for corrosion control of aluminium in acid medium. *J Appl Chem* 2014: 310–323.
45. Ali AI (2014) *Melia azedarach* L as eco-friendly corrosion inhibitor for Aluminum in 2M HCl. *J Mater Environ Sci* 5: 793–802.
46. Al-Turkustani AM, Khadijah ME (2015) Evaluating the behavior of aluminum corrosion in hydrochloric acid in the presence aqueous extract of Olive seeds. *IJIRSET* 4: 1018–1027. <https://doi.org/10.15680/ijirset.2015.0403042>
47. Pushpanjali, Rao SA, Rao P (2015) Eco friendly green inhibitor *Tinosporacordifolia* (Linn.) for the corrosion control of aluminum in sulfuric acid medium. *IJIRSET* 4: 325–333.

48. Desai PS (2017) Effect of temperature of *Calotropis Gigantea* leaves on aluminum corrosion in hydrochloric acid. *IJARSE* 6: 1055–1064.
49. Chahul HF, Ayuba AM, Nyior S (2015) Adsorptive, kinetic, thermodynamic and inhibitive properties of *Cissus populnea* stem extract on the corrosion of aluminum in acid medium. *ChemSearch J* 6: 20–30.
50. Vashi RT, Prajapati NI (2017) Corrosion inhibition of Aluminium in hydrochloric acid using *Bacopa monnieri* leaves extract as green inhibitor. *Int J ChemTech Res* 10: 221–231.
51. Prajapati NI, Vashi RT (2017) *Ocimum sanctum* (Tulsi) leaves extract as corrosion inhibitor for aluminium in hydrochloric acid medium. *IJIRSET* 6: 16376–16386.
52. Desai PS (2017) Thermodynamics of *Azardirachta indica* (Neem) leaves ark's as corrosion inhibitors for aluminum in HCl. *Int J ChemTech Res* 10: 131–138.
53. Vashi RT, Prajapati NI (2020) *Cuminum cyminum* (Jeeru) seeds extract as eco-friendly corrosion inhibitor for aluminium in HCl solution. *IJRASET* 8: 1708–1715.
54. Desai PS (2018) *Calotropis gigantea* leaves ark used as corrosion inhibitor for aluminum in hydrochloric acid. *Der Pharma Chem* 10: 7–12.
55. Al-Turkustani AM, Arab ST, Al-Dahiri RH (2010) *Aloe* plant extract as environmentally friendly inhibitor on the corrosion of aluminum in hydrochloric acid in absence and presence of iodide ions. *Mod Appl Sci* 4: 105–124. <https://doi.org/10.5539/mas.v4n5p105>
56. James AO, Odey FA (2015) Inhibitive effect of bitter kola extract on aluminium corrosion in hydrochloric acid medium. *IJSER* 6: 996–1004.
57. Ayeni FA, Alawode S, Joseph D, et al. (2014) Investigation of *Sida acuta* (wire weed) plant extract as corrosion inhibitor for aluminium-copper-magnesium Alloy in acidic medium. *J Miner Mater Charact Eng* 2: 286–291. <https://doi.org/10.4236/jmmce.2014.24033>
58. Nithya A, Santhy P, Vijaya N, et al. (2015) Inhibition of corrosion of aluminium by an aqueous extract of beetroot (betanin). *Int J Nano Corr Sci Engg* 2: 1–11.
59. Raghavendra N, Ishwara Bhat J (2018) An environmentally friendly approach towards mitigation of al corrosion in hydrochloric acid by yellow colour ripe arecanut husk extract: Introducing potential and sustainable inhibitor for material protection. *J Bio Tribo Corros* 4: 2. <https://doi.org/10.1007/s40735-017-0112-1>
60. Obi-Egbedi NO, Obot IB, Umoren SA (2012) *Spondias mombin* L. as a green corrosion inhibitor for aluminium in sulphuric acid: Correlation between inhibitive effect and electronic properties of extracts major constituents using density functional theory. *Arab J Chem* 5: 361–373. <http://doi.org/10.1016%2Fj.arabjc.2010.09.002>
61. Pushpanjali, Rao SA, Rao P (2017) Corrosion inhibition and adsorption behavior of *Murraya koenigii* extract for corrosion control of aluminum in hydrochloric acid medium. *Surf Engin Appl Electrochem* 53: 475–485. <https://doi.org/10.3103/S1068375517050088>
62. Nwosu FO, Owate IO, Osarolube E (2018) Acidic corrosion inhibition mechanism of aluminum alloy using green inhibitors. *Am J Mater Sci* 8: 45–50. <https://doi.org/10.5923/j.materials.20180803.01>
63. Nwosu OF, Osarolube E, Nnanna LA, et al. (2014) Acidic corrosion inhibition of *Piper guineense* seed extract on Al alloy. *Am J Mater Sci* 4: 178–183. <https://doi.org/10.5923/j.materials.20140404.04>

64. Kasuga B, Park E, Machunda RL (2018) Inhibition of aluminium corrosion using *Carica papaya* leaves extract in sulphuric acid. *J Miner Mater Charact Eng* 6: 1–14. <https://doi.org/10.4236/jmmce.2018.61001>
65. Chaubey N, Singh VK, Quraishi MA (2018) Papaya peel extract as potential corrosion inhibitor for Aluminium alloy in 1 M HCl: Electrochemical and quantum chemical study. *Ain Shams Eng J* 9: 1131–1140. <https://doi.org/10.1016/j.asej.2016.04.010>
66. Mejeha IM, Nwandu MC, Okeoma KB, et al. (2012) Experimental and theoretical assessment of the inhibiting action of *Aspilia africana* extract on corrosion aluminium alloy AA3003 in hydrochloric acid. *J Mater Sci* 47: 2559–2572. <https://doi.org/10.1007/s10853-011-6079-2>
67. Zaidi Mat Satar M, Farhan Mohd Noor M, Wahid Samsudin M, et al. (2012) Corrosion inhibition of aluminum by using Nipah (*Nypa fruticans*) extract solutions in hydrochloric acid (HCl) media. *Int J Electrochem Sci* 7: 1958–1967.
68. Okeke PI, Maduka OG, Emeronye RU, et al. (2015) Corrosion inhibition efficacy of *Cninosculus chayamansa* extracts on aluminum metal in acidic and alkaline media. *Int J Sci Technol* 3: 227–234.
69. Molina-Ocampo LB, Valladares-Cisneros MG, Gonzalez-Rodriguez JG (2015) Using *Hibiscus sabdariffa* as corrosion inhibitor for Al in 0.5 M H<sub>2</sub>SO<sub>4</sub>. *Int J Electrochem Sci* 10: 388–403.
70. Ajanaku KO, Aladesuyi O, Ajanaku CO, et al. (2015) Adsorption properties of *Azadirachta indica* extract on corrosion of Aluminium in 1.85 M Hydrochloric acid. *JIAATS* 16: 4.
71. Wisdom J, Kelechi D, Ugochukwu J (2018) Green inhibitor for corrosion of Aluminium alloy AA8011A in acidic environment. *IRJET* 5: 121–124.
72. Omotosho OA, Ajayi OO (2012) Investigating the acid failure of aluminium alloy in 2 M hydrochloric acid using *Vernonia amygdalina*. *ITB J Eng Sci* 44: 77–92. <https://doi.org/10.5614/itbj.eng.sci.2012.44.1.6>
73. Loto CA, Joseph OO, Loto RT (2014) Adsorption and inhibitive properties of *Camellia sinensis* for aluminium alloy in HCl. *Int J Electrochem Sci* 9: 33637–3649.
74. Olawale O, Ogunsemi BT, Agboola OO, et al. (2018) Inhibition effect of orange seed extract on aluminium corrosion in 1M hydrochloric acid solution. *IJMET* 9: 282–287.
75. Vashi RT, Prajapati NI (2019) Corrosion inhibition of aluminium in hydrochloric acid solutions by *Azadirachta indica* (Neem) leaves extract as green inhibitor. *IJGHC* 8: 444–452. <https://doi.org/10.24214/ijghc/gc/8/2/44452>
76. Anbarasi CM, Divya G (2017) A green approach to corrosion inhibition of aluminum in acid medium using Azwain seed extract. *Mater Today: Proc* 4: 5190–5200. <https://doi.org/10.1016/j.matpr.2017.05.026>
77. Pushpanjali, Rao SA, Rao P (2016) Inhibition study of *Andrographis paniculata* plants extract for the corrosion control of Aluminum in hydrochloric acid medium. *Int J ChemTech Res* 9: 291–304.
78. Al-Turkustani AM, Al-Solmi MM (2011) Corrosion inhibition of aluminum in acidic solution by aqueous extract of *Ajowan* plant as green inhibitor. *J Asian Sci Res* 1: 346–358.
79. Al-Bataineh N, Al-Qudah MA, Abu-Orabi S, et al. (2022) Use of *Capparis decidua* extract as a green inhibitor for pure aluminum corrosion in acidic media. *Corros Sci Technol* 21: 9–20. <https://doi.org/10.14773/est.2022.21.1.9>
80. Deng SD, Li XH (2012) Inhibition by *Jasminum nudiflorum* Lindl. leaves extract of the corrosion of aluminum in HCl solution. *Corros Sci* 64: 253–262. <https://doi.org/10.1016/j.corsci.2012.07.017>



81. Li XH, Deng SD (2012) Inhibition effect of *Dendrocalamus brandisii* leaves extract on aluminum in HCl, H<sub>3</sub>PO<sub>4</sub> solutions. *Corros Sci* 65: 299–308. <https://doi.org/10.1016/j.corsci.2012.08.033>
82. Krishnaveni K, Ravichandran J (2014) Effect of aqueous extract of leaves of *Morinda tinctoria* on corrosion inhibition of aluminium surface in HCl medium. *T Nonferr Metal Soc* 24: 2704–2712. [https://doi.org/10.1016/S1003-6326\(14\)63401-4](https://doi.org/10.1016/S1003-6326(14)63401-4)
83. Khadraoui A, Khelifa A, Hachama K, et al. (2016) *Thymus algeriensis* extract as a new eco-friendly corrosion inhibitor for 2024 aluminium alloy in 1 M HCl medium. *J Mol Liq* 214: 293–297. <https://doi.org/10.1016/j.molliq.2015.12.064>
84. Shah NK, Ladha DG, Wadhvani PM, et al. (2016) Corrosion inhibition performance of Coriander Seeds extract molecules for pure Aluminum in Hydrochloric acid Medium: A combined Experimental and Quantum chemical approach. *Res J Recent Sci* 5: 27–34.
85. Bashir S, Singh G, Kumar A (2017) Shatavari (*Asparagus Racemosus*) as green corrosion inhibitor of aluminium in acidic medium. *J Mater Environ Sci* 8: 4284–4291. <http://doi.org/10.26872/jmes.2017.8.12.451>
86. Ayuba AM, Abdullateef A (2021) Investigating the corrosion inhibition potentials of *Strichnos spinosa L.* extract on aluminium in 0.3 M hydrochloric acid solution. *JASES* 4: 336–348. <https://doi.org/10.48393/IMIST.PRSM/jases-v4i1.24275>
87. Petchiammal A, Selvaraj S (2013) Influence of *Cassia alata* leaves on aluminium in 1.0 N hydrochloric acid. *CJST* 1: 123–130.
88. Sharma A, Choudhary G, Sharma A, et al. (2013) Effect of temperature on inhibitory efficacy of *Azadirachta indica* fruit on acid corrosion of aluminium. *IJIRSET* 2: 7982–7992.
89. Fouda AEAS, Haleem EA (2020) Tussilago Farfara Extract (TFE) as green corrosion inhibitor for aluminum in hydrochloric acid solution. *Biointerface Res App* 10: 7023–7041. <https://doi.org/10.33263/BRIAC106.70237041>
90. Fouda AEAS, Rashwan SM, Kamel MM, et al. (2020) Juglans Regia Extract (JRE) as eco-friendly inhibitor for aluminum metal in hydrochloric acid medium. *Biointerface Res App* 10: 6398–6416. <https://doi.org/10.33263/BRIAC105.63986416>
91. Sharma S, Parihar PS, Nair RN, et al. (2012) Influence of ion-additives on inhibitory action of extract of *Trigonella foenum graceums* seeds for AA6063 in acid medium. *RJC* 5: 16–23.
92. Fouda AE-AS, Etaiw SH, Hammouda M (2017) Corrosion inhibition of aluminum in 1 M H<sub>2</sub>SO<sub>4</sub> by Tecoma non-aqueous extract. *J Bio Tribo Corros* 3: 29. <https://doi.org/10.1007/s40735-017-0090-3>
93. El-Katori EE, Al-Mhyawi S (2019) Assessment of the *Bassia muricata* extract as a green corrosion inhibitor for aluminum in acidic solution. *Green Chem Lett Rev* 12: 31–48. <https://doi.org/10.1080/17518253.2019.1569728>.
94. Onen AI, Barminas JT, Jacob J (2013) Inhibitory action of *Ficus carica* extracts on aluminium corrosion in acidic medium. *Chem Sci Trans* 2: 1326–1333. <https://doi.org/10.7598/cst2013.558>
95. Yadav S, Choudhary G, Sharma A (2013) Green Approach to Corrosion Inhibition of aluminium and copper by *Ziziphus mauritiana* fruit extract in hydrochloric acid solution. *Int J ChemTech Res* 5: 1815–1823.
96. BinYehmed FM, Abdullah AM, Zainal Z, et al. (2018) Green coffee bean extract as a green corrosion inhibitor for aluminium in artificial acid rain medium. *Int J Appl Environ Sci* 13: 171–183.

97. Orié KJ, Christian M (2015) The corrosion inhibition of aluminium metal in 0.5 M sulphuric acid using extract of breadfruit peels. *IRJET* 2: 1–9.
98. Garamon SE (2020) *Ziziphus jujube* as an eco-friendly organic inhibitor of aluminum corrosion in acidic medium. *IJGHC* 9: 9–15. <https://doi.org/10.24214/ijghc/gc/9/1/00915>
99. Ali AI, Foad N (2012) Inhibition of aluminum corrosion in hydrochloric acid solution using black mulberry extract. *J Mater Environ Sci* 3: 917–924.
100. Alinnor IJ, Ukiwe LN (2012) Evaluation of inhibitory effect of different extracts of *Vernonia amygdalina* on corrosion of aluminium in hydrochloric acid. *IJGHC* 1: 120–132.
101. Alinnor IJ, Ejikeme PM (2012) Corrosion inhibition of aluminum in acidic medium by different extracts of *Ocimum gratissimum*. *Chem Sci Int J* 2: 122–135. <https://doi.org/10.9734/ACSJ/2012/1835>
102. Dubey J, Jeengar N, Upadhyay R, et al. (2012) Corrosion inhibitive effects of *Withania Somnifera* (A medicinal plant) on aluminium in HCl solution. *Res J Recent Sci* 1: 73–78.
103. Kumpawat N, Chaturvedi A, Upadhyay RK (2012) Study on corrosion inhibition efficiency of stem alkaloid extract of different varieties of holy basil on aluminium in HCl solution. *J Korean Chem Soc* 56: 401–405. <https://doi.org/10.5012/jkcs.2012.56.4.401>.
104. Umoren SA, Eduok UM, Israel AU, et al. (2012) Coconut coir dust extract: A novel eco-friendly corrosion inhibitor for Al in HCl solutions. *Green Chem Lett Rev* 5: 303–313. <https://doi.org/10.1080/17518253.2011.625980>
105. Ladha DG, Naik UJ, Shah NK (2013) Investigation of Cumin (*Cuminum Cyminum*) extract as an eco-friendly green corrosion inhibitor for pure Aluminium in acid medium. *J Mater Environ Sci* 4: 701–708. <https://www.researchgate.net/publication/279515589>.
106. Petchiammal A, Selvaraj S (2013) Investigation of anti-corrosive effects of *Lebbeck* seed extract on aluminum in acid environment. *Pac J Sci Technol* 14: 31–39.
107. Adejo SO, Yiase SG, Ahile UJ, et al. (2013) Inhibitory effect and adsorption parameters of extract of leaves of *Portulaca oleracea* of corrosion of aluminium in H<sub>2</sub>SO<sub>4</sub> solution. *Arch Appl Sci Res* 5: 25–32. <https://www.researchgate.net/publication/274064097>
108. Adejo SO, Gbertyo JA, Ahile JU (2013) Inhibitive properties and adsorption consideration of ethanol extract of *Manihot esculentum* leaves for corrosion inhibition of aluminium in 2 M H<sub>2</sub>SO<sub>4</sub>. *Int J Mod Chem* 4: 137–146.
109. Adejo SO, Gbertyo JA, Ahile JU, et al. (2013) *Manihot esculentum* root peels ethanol extract as corrosion inhibitor of aluminium in 2 M H<sub>2</sub>SO<sub>4</sub>. *Int J Sci Eng Res* 4: 2308–2313.
110. Shalabi K, Fouda AS, Elewady GY, et al. (2014) Adsorption and inhibitive properties of *Phoenix dactylifera* L. Extract as a green inhibitor for aluminum and aluminum-silicon alloy in HCl. *Prot Met Phys Chem Surf* 50: 420–431. <https://doi.org/10.1134/S2070205114030174>
111. Al-Mhyawi SR (2014) Corrosion inhibition of aluminum in 0.5 M HCl by Garlic aqueous extract. *Orient J Chem* 30: 541–552. <https://doi.org/10.13005/ojc/300218>
112. Nair RN, Monika, Choudhary G, et al. (2014) Effect of elevation in temperature on inhibitory action of *Murraya koenigii* leaves on acid corrosion of AA6063. *Int J Adv Sci Tech Res* 4: 975–989.
113. Yiase SG, Adejo S, Ahile UJ, et al. (2014) Thermodynamic, kinetic and adsorptive parameters of corrosion inhibition of aluminium using *Sorghum bicolor* leaf extract in H<sub>2</sub>SO<sub>4</sub>. *IJARCS* 1: 38–46.

114. Dominic OO, Chikaodili AV, Sandra OC (2020) Optimum prediction for inhibition efficiency of *Sapium ellipticum* leaf extract as corrosion inhibitor of aluminum alloy (AA3003) in hydrochloric acid solution using electrochemical impedance spectroscopy and response surface methodology. *Bull Chem Soc Ethiop* 34: 175–191. <https://doi.org/10.4314/BCSE.V34I1.17>
115. Abakedi OU, Asuquo JE (2016) Corrosion inhibition of aluminium in acidic medium by ethanol leaf extract of *Azadirachta indica*. *JBAAR* 2: 556–560.
116. Njoku DI, Ukaga I, Ikenna OB, et al. (2016) Natural products for materials protection: Corrosion protection of aluminium in hydrochloric acid by *Kola nitida* extract. *J Mol Liq* 219: 417–424. <https://doi.org/10.1016/j.molliq.2016.03.049>
117. Njoku DI, Onuoha GN, Oguzie EE, et al. (2019) *Nicotiana tabacum* leaf extract protects aluminium alloy AA3003 from acid attack. *Arabian J Chem* 12: 4466–4478. <https://doi.org/10.1016/j.arabjc.2016.07.017>
118. Omotioma M, Onukwuli OD (2017) Evaluation of pawpaw leaves extract as anti-corrosion agent for aluminium in hydrochloric acid medium. *NIJOTECH* 36: 496–504. <https://doi.org/10.4314/njt.v36i2.24>
119. Ejikeme PM, Umana SG, Alinnor IJ, et al. (2014) Corrosion inhibition and adsorption characteristics of *Jatropha curcas* leaves extract on aluminium in 1M HCl. *Am J Mater Sci* 4: 194–201.
120. Raghavendra NJ, Bhat Ishwara (2017). An experimental approach towards anticorrosive potential of Areca fat species at aluminum/test solution (HCl/NaOH) interface. *Int J ChemTech Res* 10: 1003–1013.
121. Djemoui A, Souli L, Djemoui D, et al. (2017) Alkaloids extract from *Peganum harmala* plant as corrosion inhibitor of 6063 aluminium alloy in 1 M hydrochloric acid medium. *J Chem Pharm Res* 9: 311–318.
122. Iloamaeke IM, Umeobika CU, Egwuatu CI, et al. (2017) Corrosion inhibition and adsorption behaviour of aluminium in 1M H<sub>2</sub>SO<sub>4</sub> medium using *Persea americana* (avocado pear) leaves extract. *J Basic Phys Res* 7: 47–57.
123. Nnabuka EO, Awe F (2018) Experimental and quantum chemical studies on ethanol extract of *Phyllanthus amarus* (EEPA) as a green corrosion inhibitor for aluminum in 1 M HCl. *Port Electrochim Acta* 36: 231–247. <https://doi.org/10.4152/pea.201804231>
124. Suleiman IY, Abdulwahab M, Sirajo MZ (2018) Anti-corrosion properties of ethanol extract of *Acacia senegalensis* stem on Al-Si-Fe/SiC composite in sulfuric acid medium. *J Fail Anal Preven* 18: 212–220. <https://doi.org/10.1007/s11668-018-0399-3>
125. Sharma S, Sharma YC (2019) *Cordia dichotoma* as corrosion inhibitor for aluminum alloy (AA6063) in hydrochloric acid. *Port Electrochim Acta* 37: 1–22. <https://doi.org/10.4152/pea.201901001>
126. Chung I-M, Malathy R, Kim S-H, et al. (2020) Ecofriendly green inhibitor from *Hemerocallis fulva* against aluminum corrosion in sulphuric acid medium. *J Adhes Sci Technol* 34: 1483–1506. <https://doi.org/10.1080/01694243.2020.1712770>
127. Meena O, Chaturvedi A, Meena C (2019) Corrosion inhibition effect of aerial parts of *Euphorbia neriifolia* linn on aluminium in nitric acid solution. *IJGHC* 8: 801–814. <https://doi.org/10.24214/ijghc/gc/8/4/80114>

128. Meena OP, Nainawat AK, Chaturvedi A (2019) Corrosion inhibition of aluminium by alkaloid extract of aerial part of *Euphorbia neriifolia* Linn in HCl solutions. *Int J ChemTech Res* 12: 234–242. <https://doi.org/10.20902/ijctr.2019.120231>
129. Prajapati NI, Vashi RT, Desai SA (2020) Fennel (*Foeniculum vulgare* Mill) seeds extract as green inhibitor for aluminium corrosion in HCl acid solution: Thermodynamic, adsorption and kinetic study. *Eur J Biomed Pharm Sci* 7: 421–428.
130. Thacker H, Ram V (2021) *Phoenix Dactylifera L.* extracts as green corrosion inhibitor for aluminum in acidic medium. *J Sci Res* 65: 142–149. <https://doi.org/10.37398/jsr.2021.650317>
131. Meena AK, Meena AK, Sahay Bairwa B (2021) Inhibitory efficacy of *Capparis decidua* extract on the corrosion of aluminium in various acidic media. *J Adv Sci Res* 12: 254–261. <https://doi.org/10.55218/ASR.s12021121sup206>
132. Ejikeme PM, Umana SG, Onukwuli OD (2013) Corrosion inhibition of aluminium by *Treculia Africana* leaves extract in acid medium. *Port Electrochim Acta* 30: 317–328. <https://doi.org/10.4152/pea.201205317>
133. Nathiya RS, Raj V (2017) Evaluation of *Dryopteris cochleata* leaf extracts as green inhibitor for corrosion of aluminium in 1 M H<sub>2</sub>SO<sub>4</sub>. *Egypt J Pet* 26: 313–323. <https://doi.org/10.1016/j.ejpe.2016.05.002>
134. Madueke NA, Iroha NB (2018) Protecting aluminium alloy AA8011 from acid corrosion using extract from *Allamanda cathartica* leaves. *IJIRSET* 7: 10251–10258. <https://doi.org/10.15680/IJIRSET.2018.0710014>
135. Madufor IC, Itodoh UE, Obidiegwu MU, et al. (2012) Inhibition of aluminium corrosion in acidic medium by *Chrysophyllum albidum* (African star apple) fruit extract. *IOSRJEN* 2: 16–23. <http://doi.org/10.9790/3021-02951623>
136. Ramírez-Arteaga M, Valladares MG, González Rodríguez JG (2013) Use of *Prosopis laevigata* as a corrosion inhibitor for Al in H<sub>2</sub>SO<sub>4</sub>. *Int J Electrochem Sci* 8: 6864–6877.
137. Petchiammal A, Selvaraj S (2013) The corrosion control of aluminium using *Lawsonia inermis* seed extract in acid medium. *Int J ChemTech Res* 5: 1566–1574.
138. Ayuba AM, Mustapha AA (2013) Inhibitive and synergistic properties of ethanolic extract of anogeissus leiocarpus leaves on the corrosion of aluminium in HCl solution. *ChemSearch J* 4: 55–65.
139. Njoku CN, Onyelucheya OE (2015) Response surface optimization of the inhibition efficiency of *Gongronema latifolium* as an inhibitor for aluminum corrosion in HCl solutions. *Int J Mater Chem* 5: 4–13. <http://doi.org/10.5923/j.ijmc.20150501.02>
140. Prabakaran M, Kim SH, Sasireka A, et al. (2018) *Polygonatum odoratum* extract as an eco-friendly inhibitor for aluminum corrosion in acidic medium. *J Adhes Sci Technol* 32: 2054–2069. <https://doi.org/10.1080/01694243.2018.1462947>
141. Abegunde SM, Ogede RO, Oluwagbenga Fatile B, et al. (2018) Talinum triangulare leaf and *Musa sapientum* peel extracts as corrosion inhibitors on ZA-27 alloy. *J Part Sci Technol* 4: 23–28. <https://doi.org/10.22104/JPST.2018.2889.1123>
142. Ciobotaru I-E, Benga F-M, Budei D (2020) The enhancement of the corrosion resistance of aluminium and VTES-coated aluminium by using a green inhibitor. *UPB Sci Bull, Ser B* 82: 179–186.
143. Manwani N, Upadhyay RK (2019) A comparative study of inhibition efficiency of extract of leaves and stem of *Solanum xanthocarpum* on aluminium in 2N HCl solution. *IJERT* 8: 472–475.

144. Méndez-Figueroa HG, Ossandón S, Fernández JAR, et al. (2022) Electrochemical evaluation of an *Acanthocereus tetragonus* aqueous extract on aluminum in NaCl (0.6 M) and HCl (1 M) and its modelling using forward and inverse artificial neural networks. *J Electroanal Chem* 918: 116444. <https://doi.org/10.1016/j.jelechem.2022.116444>
145. Skerget M, Kenz Z, Kenz-Hrncic M (2011) Solubility of solids in sub- and supercritical fluids: A review. *J Chem Eng Data* 56: 694–714. <https://doi.org/10.1021/je1011373>
146. Xhanari K, Finšgar M, Knez Hrnčič M, et al. (2017) Green corrosion inhibitors for aluminium and its alloys: A review. *RSC Adv* 7: 27299. <https://doi.org/10.1039/c7ra03944a>
147. Welton T (2015) Solvents and sustainable chemistry. *Proc R Soc A* 471: 20150502. <http://doi.org/10.1098/rspa.2015.0502>
148. Maayta AK, Al-Rawashdeh NAF (2004) Inhibition of acidic corrosion of pure aluminum by some organic compounds. *Corros Sci* 46: 1129–1140. <https://doi.org/10.1016/j.corsci.2003.09.009>
149. Tsuru T, Haruyama S, Gijutsu B (1978) Corrosion inhibition of iron by amphoteric surfactants in 2M HCl. *J Jpn Soc Corros Eng* 27: 573–581.
150. Adejo SO, Ekwenchi MM, et al. (2014) Adsorption characteristics of ethanol root extract of *Portulaca oleracea* as eco-friendly inhibitor of corrosion of mild steel in H<sub>2</sub>SO<sub>4</sub> medium. *IOSR-JAC* 7: 55–60. <https://doi.org/10.9790/5736-07415560>
151. Eddy NO, Ebenso EE (2008) Adsorption and inhibitive properties of ethanol extracts of *Musa sapientum* peels as a green corrosion inhibitor for mild steel in H<sub>2</sub>SO<sub>4</sub>. *Afr J Pure Appl Chem* 2: 46–54.
152. Obot IB, Obi-Egbedi NO, Umoren SA, et al. (2010) Synergistic and antagonistic effects of anions and *Ipomoea invulcrata* as green corrosion inhibitor for aluminium dissolution in acidic medium. *Int J Electrochem Sci* 5: 994–1007.
153. Ebenso EE (2003) Effect of halide ions on the corrosion inhibition of mild steel in H<sub>2</sub>SO<sub>4</sub> using methyl red: Part 1. *Bull Electrochem* 19: 209–216.
154. Ating EI, Umoren SA, Udousoro II, et al. (2010) Leaves extract of *Ananas sativum* as green corrosion inhibitor for aluminium in hydrochloric acid solutions. *Green Chem Lett Rev* 3: 61–68. <https://doi.org/10.1080/17518250903505253>
155. Dehri I, Ozcan M (2006) The effect of temperature on the corrosion of mild steel in acidic media in the presence of some sulphur-containing organic compounds. *Mater Chem Phys* 98: 316–323. <https://doi.org/10.1016/j.matchemphys.2005.09.020>
156. Singh MR, Bhrara K, Singh G (2008) The inhibitory effect of diethanolamine on corrosion of mild steel in 0.5 M sulphuric acidic medium. *Port Electrochim Acta* 26: 479–492.
157. Agrawal D, Gupta KD, Saxena KK (2003) Thermodynamics and equilibrium study of the formation of binary and tertiary complexes of Co<sup>+2</sup>, Ni<sup>+2</sup>, Cu<sup>+2</sup> and Zn<sup>+2</sup> with (DL)-2,5 Diamino -1-pentanoic acid as secondary ligand and 2',2'-Biperidine (2',2'-Bipy) as primary ligand. *Trans SAEST* 38: 111–114.
158. Issa RM, El-Sonbati AZ, El-Bindary AA, et al. (2008) Polymer complexes XXXIV. Potentiometric and thermodynamic studies of monomeric and polymeric complexes containing 2-acrylamidosulphadiazine. *Eur Polym J* 38: 561–566.
159. Khaled KF, Al-Qahtani MM (2009) The inhibitive effect of some tetrazole derivatives towards Al corrosion in acid solution: Chemical, electrochemical and theoretical studies. *Mater Chem Phys* 113: 150–158. <https://doi.org/10.1016/j.matchemphys.2008.07.060>

160. Amin MA, Mohsen Q, Hazzai OA (2009) Synergistic effect of  $\Gamma^-$  ions on the corrosion inhibition of Al in 1.0 M phosphoric acid solutions by purine. *Mater Chem Phys* 114: 908–914. <https://doi.org/10.1016/j.matchemphys.2008.10.057>
161. Noor EA (2009) Evaluation of inhibitive action of some quaternary N-heterocyclic compounds on the corrosion of Al–Cu alloy in hydrochloric acid. *Mater Chem Phys* 114: 533–541. <https://doi.org/10.1016/j.matchemphys.2008.09.065>
162. Valand T, Heusler KE (1983) Reactions at the oxide-electrolyte interface of anodic oxide films on aluminum. *J Electroanal Chem Interfacial Electrochem* 149: 71–82. [https://doi.org/10.1016/S0022-0728\(83\)80559-2](https://doi.org/10.1016/S0022-0728(83)80559-2)
163. Singh AK, Quraishi MA (2010) Effect of Cefazolin on the corrosion of mild steel in HCl solution. *Corros Sci* 52: 152–60. <https://doi.org/10.1016/j.corsci.2009.08.050>
164. Abd El Rehim SS, Hassan HH, Amin MA (2001) Corrosion inhibition of aluminum by 1,1(lauryl amido)propyl ammonium chloride in HCl solution. *Mater Chem Phys* 70: 64–72. [https://doi.org/10.1016/S0254-0584\(00\)00468-5](https://doi.org/10.1016/S0254-0584(00)00468-5)
165. Amin MA, Khaled KF, Mohsen Q, et al. (2010) A study of the inhibition of iron corrosion in HCl solutions by some amino acids. *Corros Sci* 52: 1684–1695. <https://doi.org/10.1016/j.corsci.2010.01.019>
166. McCafferty E, Hackerman N (1972) Double-layer capacitance of iron and corrosion inhibition with polymethylene diamines. *J Electrochem Soc* 119: 146. <https://doi.org/10.1149/1.2404150>
167. Umoren SA, Solomon MM (2015) Effect of halide ions on the corrosion inhibition efficiency of different organic species—A review. *J Ind Eng Chem* 21: 81–100. <https://doi.org/10.1016/j.jiec.2014.09.033>
168. Umoren SA, Obot IB, Ebenso EE (2008) Corrosion inhibition of aluminium using exudate gum from *Pachylobus edulis* in the presence of halide ions in HCl. *J Chem* 5: 138407. <https://doi.org/10.1155/2008/138407>
169. Umoren SA, Ekanem UF (2010) Inhibition of mild steel corrosion in  $H_2SO_4$  using exudate gum from *Pachylobus edulis* and synergistic potassium halide additives. *Chem Eng Commun* 197: 1339–1356. <https://doi.org/10.1080/00986441003626086>



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