http://communications.science.ankara.edu.tr

Commun. Fac. Sci. Univ. Ank. Ser. B Chemistry and Chemical Engineering
Volume 64, Number 1, Pages 20-79 (2022)
ISSN 1303-6017 E-ISSN 2687-4806
http://dergipark.org.tr/en/pub/communb/issue/68523/1109768

Review Article; Received: April 27, 2022; Accepted: June 30, 2022

PLANT EXTRACTS AS CORROSION INHIBITORS FOR ALUMINUM IN ACIDIC ENVIRONMENTS- REVIEW I

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ABSTRACT. The use of plant extracts as inhibitors in corrosive environments has been the subject of many studies in recent years. This review presents studies with various plant extracts used as inhibitors of the corrosion of aluminum in acidic environments.

1. INTRODUCTION

Corrosion is defined as the deterioration of substances, especially metals and alloys, resulting from chemical and electrochemical changes with various effects on the environment. Corrosion waste products stop production and cause serious accidents and significant economic losses in various industrial sectors. Therefore, it is an undesirable event, and it is tried to be prevented. There are several methods for reducing or preventing corrosion, such as anodic and cathodic protection, coatings, and the usage of inhibitors. Inhibitors are organic or inorganic compounds that reduce or prevent corrosion by adding small amounts in corrosive environments.

Many studies showed that synthesized organic or inorganic compounds could inhibit the corrosion process [1-16]. However, most of these compounds are highly toxic and harmful to the environment and human health. Therefore, in recent years scientists have focused on corrosion prevention methods using green inhibitors especially plant extracts [17-36]. Plant extracts are non-toxic, biodegradable, inexpensive, and not harmful to the environment and human health. Plant extracts contain many organic compounds, having polar atoms such as O, P, S, and N.

Keywords. Aluminum, corrosion, plant extracts, acidic media, inhibitors

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These polar atoms and protective films are formed by these compounds adsorb on the metal surface.

Aluminum is the most used metal after iron because of its low atomic mass, the negative value of standard electrode potential, and corrosion resistance. Aluminum by itself is not resistant to corrosion; however, it can be easily covered in the air and becomes highly resistant to corrosive attacks in various media. Nevertheless, exposed to acidic, alkali, and chloride-containing media, the protective oxide layer on aluminum is damaged, exposing the aluminum materials to attack the corrosive environment.

In this review study, plant extracts as corrosion for aluminum in acidic mediums are summarized.

2. THE STUDIES IN ACIDIC ENVIRONMENTS

Bashir et al. determined the corrosion inhibition effect of *Origanum vulgare* (*oregano*) for aluminum in a 1 M HCl medium. The weight-loss method, quantum chemical analysis, and SEM technique were applied to determine the inhibition properties of the extract. It was seen that inhibition efficiency of *Origanum vulgare* varied directly with its concentration and inversely with temperature. The maximum inhibition efficiency of 97.7% was found at 4000 ppm of extract. The adsorption of the extract followed Langmuir isotherm. Quantum chemical studies were used to determine the molecular structure and to elucidate the electronic structure and reactivity of the inhibitor [37].

Ejikeme et al. investigated the inhibitive effect of *Treculia africana* leaves extracts in aluminum corrosion in 1M HCl. The researchers studied using weight loss and thermometric methods at 30-60°C. The results showed that *Treculia africana* acted as a corrosion inhibitor of aluminum in HCl. The inhibition efficiency increased with an increase in extract concentrations but decreased with an increase in temperature [38]. The interaction of extract with the aluminum surface was found to obey Freundlich and El-Awady adsorption isotherms, and first-order kinetics was followed. The inhibition efficiency of ethanolic extract of different parts of *Capparis decidua* in acidic environments has been investigated by Arora et al. [39]. The researchers studied in 0.5 N H_2SO_4, 1 N H_2SO_4, 2 N H_2SO_4, and 3N, 4N, and 5N HCl environments. The researchers used mass loss and thermometric methods. It was found that the corrosion rate of aluminum in sulphuric acid and hydrochloric acid is a function of the concentration of *Capparis decidua*. This ethanolic extract can be used instead of toxic chemicals. Chaukan et al. published the inhibition of aluminum corrosion in acid solution by methanol extract of *Citrullus colocynthis* plant [40]. The authors studied using mass loss and thermometric measurements. Acid concentrations were selected as 3N, 4N, and 5N for hydrochloric acid and sulphuric acid. The plant extract has been found to act as a suitable corrosion inhibitor for all concentrations of sulphuric acid and hydrochloric acid studies. From experimental results, it was found that inhibition efficiency increase with increasing inhibitor concentration. The study of the extract of plant *Citrullus colocynthis* in different acid concentration solutions has proved them to be effective inhibitors of aluminum corrosion, giving up 87.2%. It was determined that the adsorption of the extract on aluminum obeyed Langmuir adsorption isotherm.

The inhibition effect of *Adhadota vasika* alkaloids on aluminum corrosion in hydrochloric acid, sulphuric acid, and phosphoric acid solutions has been investigated by Chandrasekaran and Sankar [41]. In this study, the mass loss technique was employed at 302-333 K. The inhibition efficiency increased with an increase in the concentration of inhibitor and decreased with a rise in temperature from 302 to 333 K. The adsorption of this extract on the aluminum surface from the acids has been found to obey the Temkin adsorption isotherm. The Opuntia extract's inhibitive effect on aluminum's corrosion was studied in a 2M HCl solution by A. Y. Etre [42] using weight loss, thermometry, and polarization techniques. It was found that the inhibition efficiency increases as the extract concentration are increased; however, with the increase in temperature, the inhibition efficiency values decrease. The inhibition action is performed via adsorption of the extract on the aluminum surface. According to the experimental findings, the adsorption process is spontaneous and follows the Langmuir adsorption isotherm. The presence of *Opuntia* extract increases the activation energy of the corrosion reaction. The extract provides some protection against the pitting corrosion of aluminum in the presence of chloride ions. The degree of protection increases with increasing *Opuntia* extract concentrations. The leaf extracts of *Chlomolaena odorata* L have been studied as a possible source of green inhibitor for aluminum corrosion in HCl by Obot and Obi-Egbedi [43]. The researchers used gasometric and thermometric techniques at 30°C and 60°C. The inhibition efficiency increased with extract concentration but decreased with temperature. The adsorption of the extract is in accordance with the Langmuir adsorption isotherm. This study provides new information on the inhibiting characteristics of the extract under specified conditions. According to the experimental findings, the phenomenon of physical adsorption occurs. Corrosion inhibition of aluminum in 1 M HCl by *Coconut coir dust* [44] extract was studied using weight loss and hydrogen evaluation techniques at 30°C and 60°C. It was found that this extract exhibits a very good performance as an inhibitor for aluminum corrosion in 1 M HCl. Results showed that the inhibition efficiency increases with the increasing temperature and concentration of the extract. An inhibitive effect was afforded by adsorption of the extract, which was found to accord with Langmuir adsorption isotherm.

Ating et al. determined the inhibition of corrosion of aluminum in hydrochloric acid solutions by the ethanolic extract of the leaves of *Ananas sativum* using weight loss and hydrogen evolution methods [45]. It was found that inhibition efficiency increased with increasing extract concentration and temperature. Adsorption studies revealed that Langmuir adsorption isotherm is the best adsorption model applicable to the adsorption of *Ananas sativum* on an aluminum surface. Activation parameters such as activation energies E_a, activation enthalpy ΔH, and activation entropy ΔS were calculated from the effect of temperature on the corrosion and inhibition processes. The values of adsorption free energies $\Delta G°_{ads}$ determined are low and negative, which reveals the spontaneity of the adsorption process. Deng and Li investigated the inhibition effect of *Jusminum nudiflorum Lindl* leaves extract on the corrosion of aluminum in 1.0 M HCl solution [46]. The researchers applied weight loss, polarization curves, electrochemical impedance spectroscopy (EIS), and scanning electron microscopy (SEM) methods. According to polarization curves, the extract acts as the cathodic inhibitor. The adsorption of the extract obeys Langmuir adsorption isotherm.

Inhibition of aluminum corrosion in HCl solutions by *Ficus carica* [47] leaf extract was determined using weight loss measurements at 303, 313, 323, and 333 K. Increase in temperature increased corrosion rate but decreased inhibition efficiency. The adsorption of the extract on the aluminum surface followed Frumkin and Langmuir's adsorption isotherm. According to the kinetic data, adsorption follows the first-order type of reaction. Halambek et al. studied the ethanol solution of *Ocimum basilium L* [48] oil was studied as a corrosion inhibitor for aluminum in 0.5M HCl. Its inhibition effect was performed using weight loss measurements, potentiodynamic polarization, and EIS methods.

Ladha et al. investigated the inhibitive effect of C*umin* extract as a corrosion inhibitor for pure aluminum in 1 N HCl has been investigated by using weight loss, galvanostatic polarization, and electrochemical impedance spectroscopy (EIS) techniques [49]. The results reveal that inhibition efficiency increases with an increase in the concentration of inhibitor but decreases with an increase in temperature. The *Cumin* extract acts as a mixed type inhibitor with a predominance of cathodic inhibitor on pure aluminum surface. Electrochemical impedance spectroscopy result shows that the charge transfer resistance increases and double layer capacitance decreases with an increase in the concentration of inhibitor. The adsorption of inhibitor obeys Langmuir adsorption isotherm.

Madufor et al. studied the inhibition of aluminum corrosion in 0.002 M H_2SO_4 solution in the absence and presence of fruit extract from *Chrysophyllum Albidum* (African Star Apple) at a temperature range of 30-60°C using weight loss and thermometric techniques [50]. The inhibition efficiency increased with an increase in inhibitor concentration but decreased with an increase in temperature. The inhibiting effect of the *Chrysophyllum albidum* fruit extract could be attributed to the presence of some phytochemical constituents in the fruit extract, which is adsorbed on the surface of the aluminum. The fruit extract from *Chrysophyllum albidum* was found to obey the Temkin adsorption isotherm. Thermodynamic parameters reveal that the adsorption process is spontaneous.

The protective effect of *Cassia auriculata* against aluminum corrosion was investigated by Rajendran et al. in 2 M HCl at 30±1°C by weight loss, polarization study, and impedance methods [51]. It was ascertained that the percentage of inhibition increases with the increase in the concentration of the extract. The maximum inhibition efficiency was found at 44.07% by the weight-loss method, 97.27% by the Tafel method, and 72.38% by the linear polarization method, respectively, in 1.0 (%v/v). The corrosion inhibition of aluminum in 0.5 MH_2SO_4 solutions in the presence of *Velvet Tamarind -Water* extract was investigated by James and Osarolube using a weight loss technique at the temperature range of 30-50° C [52]. It was found that the inhibition efficiency of *Velvet Tamarind -Water* extract increased with an increase in temperature and the concentration of the extract. The inhibition may be attributed to the adsorption of the active ingredients in extract on the aluminum surface. The adsorption fits well into the Langmuir adsorption isotherm. Awea et al. determined the extracts of *Boscia senegalensis* x as corrosion inhibitors for aluminum in 1 M HCl solution using gravimetric and linear polarization methods [53]. The results from gravimetric measurements show an increase in inhibition efficiency with an increment in extract concentration. Linear polarization results illustrate that the mode of inhibition was a mixed type. The observed decrease in corrosion rate was due to the adsorption of the extract on the aluminum surface, which obeys the Langmuir adsorption isotherm.

Li and Deno reported the inhibition effect of *Dendrocalamus brandisil* leaves extract on aluminum corrosion in HCl and H_3PO_4 solutions [54]. The authors studied weight loss, potentiodynamic polarization, and electrochemical impedance spectroscopy (EIS) methods. Effects of temperature and extract concentration were investigated. The results show that *Dendrocalamus brandisil* leaf extract is a good inhibitor in 1.0 M HCl while a moderate inhibitor in H_3PO_4. The adsorption of the inhibitor on the aluminum surface obeys Langmuir adsorption in both acids. The corrosion inhibition of aluminum in sulfuric acid solution in the presence of the ethanolic extract of *Calotopis procera* and *Alotropis gigentea* different plant parts, namely leaves, latex, and fruit, was studied by Kumar and Mathur using the weight loss method and thermometric method [55]. The ethanolic extracts of *Calotropis procera* and *Calotropis gigantea* act as an inhibitor in different sulphuric acid concentrations such as 0.5 N, 1.0 N, 2.0 N, 3.0 N, 4.0 N, and 5.0 N sulphuric acid. The inhibition efficiency increases with an increase in inhibitor concentration. The plant parts inhibit aluminum, and inhibition is attributed to the adsorption of the plant part on the aluminum surface. The inhibitive action of ethanol leaf extract of *Sorghum bicolor* [56] has been published by Yiase et al. using the weight loss method at the temperature range of 305K to 315K. In the study, the inhibitive action was observed to increase with increased concentration of the extract, but decreased with increased temperature. Adsorption of leaf extract of *Sorghum bicolor* best fitted into the Frumkin, El-Awady isotherms, and Adejo-Ekwenchi isotherm models and mechanism of adsorption is physisorption.

Norzila et al. studied the corrosion inhibition of aluminum in 0.1 M HCl by *Nephelium Lappaceum* (*Rambutan*) peel extract [57]. The scientists applied gravimetric and thermometric methods. Obtained data from gravimetric and thermometric results have shown that the value of inhibition efficiency is proportional to the added inhibitor concentration and inversely proportional to the temperature. Occurred inhibition mechanism was in the form of inhibitor adsorption on the aluminum surface that allegedly proceeded by physical adsorption. The SEM study also confirmed the adsorption of extracted inhibitor molecules onto the aluminum surface. Ladha et al. published the study that contains the corrosion inhibition and adsorption behavior of *black pepper* extract on pure aluminum in a 1 M hydrochloric acid medium [58]. The authors made a combined experimental and computational study using gravimetric, electrochemical impedance spectroscopy, galvanostatic polarization, scanning electron microscopy with energy dispersive X-ray examination (SEM-EDX) techniques, quantum chemical calculations (density functional theory). The gravimetric measurement reveals that inhibition efficiency illustrates direct proportional relation with a concentration of the inhibitor. The impedance results show that there was a presence of a protective layer of inhibitor adsorbed on the metal/solution interface. Polarization results showed that *black pepper* extract is mixed type inhibitor. The existence of adherent layer of inhibitor on the Al surface was confirmed by SEM-EDX. Quantum chemical calculations were performed using the density functional theory of B3LYP76-31G (d) level of theory to evaluate the activity of inhibitor molecules in extract towards the corrosion inhibition of Al.

Nnanna et al. investigated the inhibition properties of *Newbouildia leavis* leaf extract on the corrosion of aluminum in 0.2-1.0 M HCl and 0.1-1.0 M H_2SO_4 solutions using the gravimetric technique [59]. The results show that *Newbouldia leaves* are a good inhibitor and exhibit more efficiency in 1.0 M HCl than 0.5 M H_2SO_4. It was revealed that the presence of an inhibitor inhibited the corrosion of aluminum in the test solutions and the inhibition efficiency depended on the concentration of the plant extract as well as on the time of exposure of the aluminum samples in H_2SO_4 solutions containing the extract. The experimental data complied with the Langmuir adsorption isotherm, and the value and sign of the Gibbs free energy of adsorption suggested that inhibitor molecules have been spontaneously adsorbed onto the aluminum surface through a physical adsorption mechanism. The adsorption of *Newbouldia leavis* leaf extract on the aluminum surface obeys Langmuir adsorption isotherm.

Prabhu and Rao reported the corrosion inhibition characteristics of aqueous extract of seeds of *Coriandrum sativum* Las an eco-friendly green inhibitor for corrosion control of aluminum in 1 M phosphoric acid solution [60]. The authors used potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) techniques. In the study, the effects of inhibitor concentration and temperature on the inhibition action were investigated. The inhibition efficiency of the *Coriandrum sativum* L extract increases with an increase in the concentration of inhibitor; however, it decreases with an increase in the temperature. The extract acts as a mixed-type inhibitor by inhibiting both cathodic and anodic leaf extract reactions to the same extent. It has been shown that the adsorption of the extract on the surface of aluminum follows the Langmuir adsorption isotherm. The value of activation energy suggests that *Coriandrum sativum* L undergoes physical adsorption on the aluminum surface. The corrosion inhibition efficiency of *Dryopteris cochleata*, leaf extract was investigated by Nathia and Raj by using various methods such as weight loss, electrochemical measurement, X-ray diffraction, and scanning electron microscopy [61]. The plant extract was characterized using Fourier transform infrared spectroscopy, X-ray diffraction, and SEM analysis. Methanol and water extracts of *Dryopteris cochleata* leaves act as an inhibitor for aluminum corrosion in a 1 M H_2SO_4 solution. According to the experimental results, inhibition efficiency increases with an increase in the concentrations of inhibitors but decreases with a temperature rise. All the techniques employed are in reasonably good agreement, pointing to the fact that the methanol extract of *Dryopteris cochleata* leaves is a better inhibitor than water extracts within the range of the concentrations investigated. The adsorption of the inhibitors on the aluminum surface obeys the Freundlich adsorption isotherm. The adsorption free energy of the inhibitors on the aluminum surface indicates the physisorption type of inhibitor. XRD and SEM images confirm the protective film formation on the aluminum surface.

The inhibition efficiency of *Phoenix Dactylifera L extract* has been proved in two different studies [62-63]. Shalabi et al. illustrated the inhibition efficiency of alcoholic extract of *Phoenix Dactylifera L* plant on aluminum in 0.5 M HCl solution by potentiodynamic polarization, electrochemical impedance spectroscopy (EIS), and electrochemical frequency modulation (EFM) methods [62]. The results obtained for all electrochemical measurements showed that inhibiting properties increase with inhibitor concentration and decrease with the temperature. The extract prevents the corrosiıon of aluminum and acts as a mixed type inhibitor but dominantly acts as a cathodic inhibitor in 0.5 M HCl medium. The adsorption of inhibitor for aluminum surface follows Langmuir isotherm. Thacker and Ram indicated the corrosion inhibition of aluminum in 1 N HCl medium using male and female *Phoenix Dactylifera L* leaves extracts by weight loss measurement in the temperature range 313-333 K [63]. The efficiency of the inhibitor increases with an increase in inhibitor dosage from 8 to 40 gL^{-1} and decreases with an increase in the temperature from 30°C to 60°C. The inhibitor efficiencies were determined at 88.70% and 95.16% for male and female extracts, respectively, at an inhibitor dosage of $40gL^{-1}$. The corrosion inhibition process for both extracts is well fitted to the Langmuir adsorption isotherm indicating for monolayer formation of inhibitor molecules on the aluminum surface.

The corrosion inhibitive effects of *Aningeria robusta* extract for aluminum in 2 M HCl solution and the influence of potassium iodide additives on the inhibition efficiency were assessed by Obot et al. using the hydrogen evolution method at 30°C and 60°C [64]. The inhibition efficiency was determined by comparing the corrosion rates in the absence and presence of additives. The trend of inhibition efficiency with temperature was used to propose the mechanism of inhibition. It was found that the *Aningeria robusta* extract acts as an inhibitor for acid-induced aluminum corrosion. The inhibition efficiency (I%) of the extract increased with an increase in concentration and with an increase in temperature of the *Aningeria robusta* extract.

On the other hand, inhibition efficiency (%I) synergistically increased with the addition of potassium iodide but decreased with increased temperature. Inhibitor adsorption characteristics were approximated by Langmuir adsorption isotherm at all the concentrations and temperatures studied. The mechanism of chemical adsorption is proposed for the *Aningeria robusta* extract and physical adsorption of the extract-iodide mixture from the trend of inhibition efficiency with temperature and the calculated values of activation energy and heat of adsorption. The inhibition of aluminum corrosion in 0.5 M hydrochloric acid by *Ajowan* plant was studied by Turkustani and Solmi using chemical (weight loss) and electrochemical (impedance and polarization) methods [65]. The *Ajowan* plant extract was found to be a suitable inhibitor for aluminum corrosion in 0.5 M hydrochloric acid in the studied concentration range of inhibitor. Corrosion inhibition could be explained by considering the interaction between the metal surface and the inhibitor molecules. Electrochemical measurements showed that *Ajowan* inhibitor affects both cathodic and anodic Tafel slopes in HCl medium and acts as mixed-type inhibitor. The adsorption of *Ajowan* extract on the aluminum surface from HCl follows the Langmuir adsorption model.

O.Obi-Egbedi et al. revealed the inhibition of aluminum in 0.5 M H_2SO_4 by extracts of *Spondias mombin L* [66]. The scientists investigated using the standard gravimetric technique at 30-60°C. It was found that the *Spondias mombin L* extracts act as an inhibitor for acid-induced aluminum corrosion. The inhibition efficiency of the extract increased with an increase in the concentration of the extract but decreased with temperature. Furthermore, inhibition efficiency synergistically increased on the addition of potassium iodide.

S*pondias mombin L*. extract alone and in combination with the potassium iodide can be approximated by the Langmuir adsorption isotherm at all the concentrations and temperatures studied. It has been found that activation energies were higher in the presence of *Spondias mombin* l. the extract shows physisorption and adsorption process is spontaneous, exothermic, and accompanied by a decrease in entropy of the system from a thermodynamic point of view. In the study, quantum chemical calculations were performed using the density functional theory at the B3lYP/6-31G(d) level of theory to find out whether a clear link exists between the inhibitive effect of the extract and the electronic properties of its main constituents. R.Al-Mhyawi published the corrosion inhibition of aluminum in 0.5 M HCl by *aqueous garlic* extract [67]. The author evaluated the inhibition property of the extract by weight loss technique. Values of inhibition efficiency obtained are dependent upon the concentrations of inhibitor and temperature. Generally, inhibition was found to increase with inhibitor concentration but decrease with temperature. The adsorption of different concentrations of the *garlic* extract on the surface of aluminum in 0.5M HCl acid followed both Langmuir and Temkin adsorption isotherm. The values of standard free energy of adsorption suggest that the adsorption of inhibitor on the aluminum surface occurred by physisorption mechanism; the negative sign of the free energy of adsorption shows that the adsorption of the extract on the aluminum surface was a spontaneous process. In another study, the effect of *garlic* on the anticorrosive protection properties of aluminum and vinyl-trietoxysilane (VTES)-coated aluminum by Cıabotaru et al. using the electrochemical impedance spectroscopy (EIS) technique [68]. The experiments were carried out in 0.05 M phosphoric acid (H_3PO_4) solution at different temperatures (30°C and 40°C). The values of the polarization resistance increase with increasing the concentration of the *garlic* extract for a given temperature. The results showed that the VTES – coated aluminum has better corrosion resistance. If the effect of temperature is investigated, it is seen that the VTES-coating increases the polarization resistance by up to 4 times for the samples analyzed at 30°C and up to 3 times for the one analyzed at 40°C. The inhibiting effect of the *garlic* extract has lower values at a temperature of the corrosive media of 40°C compared to 30°C. For the VTES-coated aluminum, the inhibition efficiency of the *garlic* extract increases with the temperature of the corrosive media; values over 90% were determined.

Sharma et al. investigated the corrosion of aluminum in different concentrations of HCl solution by mass loss and thermometric method in the absence and presence of the alcoholic extract of *Prosopis cineraria* [69]. From the mass loss data, it is concluded that the inhibition efficiency increased with the increase in inhibitor concentrations. The alcoholic extract of *Prosopis cineraria* was found to be an effective corrosion inhibitor giving up 96.93% efficiency, and can be safely used without toxic effects and pollution.

The inhibition efficiency of acetone extract of *red onion skin* on aluminum in 2 M hydrochloric solutions was reported by James and Akarantsa [70]. The authors used the weight loss technique for determining the corrosion parameters. The results of the study can be summarized as follows: Acetone extract of *red onion skin* is an effective inhibitor of the corrosion of aluminum in 2M hydrochloric acid solution at 303, 313, and 323 K. The inhibitor efficiency increases with increased inhibitor concentration and decreased temperature. Mechanism of physical adsorption was proposed, and the first-order type of reaction was obtained from the kinetic treatment of the data. Acetone extract of red onion skin obeys Langmuir adsorption isotherm at all studied temperatures on aluminum in 2 M hydrochloric acid. In another study, James and Akaranta showed that the corrosion rate of aluminum in 2M sulphuric acid is a function of the concentration of the acetone extract of *red onion skin* [71]. The researchers used hydrogen gas evolution and weight loss techniques to determine the corrosion rates. The experiments were carried out at temperatures of 30°C, 40°C, and 50°C. The inhibition efficiency was found to increase with increasing inhibitor concentration and decreasing temperature. The inhibition is attributed to the adsorption of *red onion skin ext*ract on the aluminum surface, and the adsorption obeys the Langmuir adsorption isotherm. Nnaji et al. determined the characterization of *red onion skin tannin* as a corrosion inhibitor for aluminum in different concentrations of HCl [72]. *Red onion skin tannins* were found to be an effective corrosion inhibitor of aluminum in hydrochloric acid solutions using gravimetric, thermometric, and UV/visible spectrometric techniques. The extract adsorption of aluminum followed Langmuir isotherm in 0.1 M, and Freundlich isotherm in 0.5 M HCl and 2 M HCl at 303 K. Temperature variation studies reveal that inhibition efficiency decreases as temperature increases. Determination of free energy of adsorption of the *red onion skin tannin* on aluminum was from obtained adsorption parameters and gave value characteristic of physisorption.

The corrosion inhibition of aluminum in HCl solution in the presence of exudate gum from *Raphia hookeri* at a temperature range 30-60°C was studied by Umoren et al. [73]. The researchers applied weight loss and thermometric techniques. According to the experimental findings, the inhibition efficiency increases with an increase in inhibitor concentration but decreases with an increase in temperature. The inhibitive effect of the *Raphia hookeri* exudate could be attributed to the presence of some phytochemical constituents in the exudate, which is adsorbed on the aluminum surface. Umoren and Ebenso investigated the effect of *Raphia hookeri* exudate gum and halide ions on the corrosion inhibition of aluminum in HCl solutions at 30-60°C and studied the mechanism of action [74]. In this study, the corrosion rates were determined using gravimetric (weight loss), gasometric (hydrogen evolution), and thermodynamic techniques. Results showed that the Raphia hookeri exudates gum acted as an inhibitor for aluminum corrosion in an acidic environment. The inhibition efficiency increased with an increase in the concentration of the *Raphia hookeri* exudates gum and synergistically increased to a considerable extent on the addition of halide ions. The increase in inhibition efficiency (I%) and surface coverage (ϴ) in the presence of halides were found to order $I^->Br^-> Cl^-$ which indicates that the radii, as well as electronegativity of halide ions, play a significant role in the adsorption process. *Raphia hookeri* exudates gum obeys Freundlich, Langmuir and Temkin adsorption isotherms. The phenomenon of physical adsorption is proposed from the values of kinetic/thermodynamic parameters.

Corrosion inhibition of aluminum using flower extract of *Marigold* (*Tagetes erecta L*) in 0.5M HCl solution was determined by Obruche et al. [75]. The researchers applied the weight loss technique. The corrosion rate was found to decrease tremendously, and it was also observed that the inhibition efficiency increased with an increase in the volume of the extracts. The maximum values of the inhibition efficiency of 81.8%, 87.3%, 90.2% the concentration of 1.1ml, 2.3 ml, and 3.4 ml for 5 hours of immersion time, respectively. The corrosion inhibition is probably due to the adsorption of the phytochemical constituents of the extract and the blocking of its active sites by the phenomenon of chemical adsorption. Olusegun and Tobun investigated the ability of *Cocus nuclifera* L water as a non-toxic corrosion inhibitor for aluminum corrosion in 0.5 M HCl using a chemical technique [76]. Experimental results show *Cocus nucifera* L was significant inhibition as a corrosion inhibitor for this acid corrosion with 93% efficiency at the highest concentration of the inhibitor. This inhibitive action was attributed to the adsorption of inhibitor molecules on the metal surface following the Langmuir adsorption isotherm.

When we look at the literature, studies are showing that *Vernonia amydalina* (*bitter leaf)* acts as an effective inhibitor in acidic environments [77-79]. Corrosion inhibitor effect of extract of *Vernonia amygdalina* on aluminum was studied using the gravimetric method [77]. Kolawole et al. revealed that the extract could be used as an eco-friendly corrosion inhibitor for aluminum in a 0.5 M HCl solution. The corrosion inhibition efficiency of the extract increases with its concentration in this corrosion media. Surface coverage of the extract obeyed Langmuir adsorption isotherm. Oluseyi et al. studied the corrosion inhibition effect of *Vernonia amydalina* extract on aluminum in a 0.5M HCl solution. In this study gravimetric method was used at 40°C [78]. Aluminum samples of dimensions 3x1.5 cm were immersed in test solutions of uninhibited acid and those containing extract concentrations of 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0 g/L at intervals of 30 minutes progressively for 150 minutes. The corrosion rate of aluminum in 0.5 M HCl solution containing extract decreases with an increase in the concentration of the inhibitor. In another study, the inhibition efficiency of ethanolic extract of *Vernonia amygdalina* extract on aluminum in 1M HCl solutions was determined by weight loss technique [79]. Dauda et al. showed that the corrosion of the aluminum samples in a 1.0 M HCl medium decreased with an increased period of exposure due to the passivation of the surface by $AlCl_3$. The percentage inhibition efficiency increased with the concentration of the extract but decreased with temperature. A physical adsorption mechanism has been proposed for the inhibition, and Langmuir adsorption isotherm was obeyed.

Olewale et al. investigated the inhibition effect of *orange seed* extract on aluminum corrosion using weight loss measurement and phytochemical analysis [80]. The study was made at a temperature of 30°C with a concentration of inhibitor varied from 0-0.3 g/l in 1M HCl medium for 10 days. It was observed that the corrosion rate increases as the concentration of inhibitor decrease with time. It can be concluded from the study that *Orange* seed extract is a good eco-friendly corrosion inhibitor for aluminum in 1M HCl solution. Ukpe revealed that ethanol extract of *Orange peel* contains corrosion inhibitors that combine to exert corrosion inhibitive action on aluminum [81]. The researcher used the weight loss method. The inhibition efficiency increased with increasing concentration while decreased with increasing temperature. The extract is an adsorption inhibitor that follows a physisorption mechanism. However, in the presence of halide ions, the mechanism changes to chemisorption at higher temperatures. The joint effect of halides and *Orange peel* waste gave better ideality to the Langmuir adsorption model. Calculated synergistic parameters were more remarkable than unity indicating that the adsorption of ethanol extract on *Orange peel* waste was enhanced by synergistic interaction with halides. The prevalence of the physical adsorption mechanism was confirmed through free energy of adsorption obeyed Langmuir isotherm.

Olewale et al. investigated the optimization of *almond* leaves extract as a corrosion inhibitor on aluminum in 1 M HCl. The effect of temperature (30-50°C), inhibitor concentration (0.2g/l-0.6g/l), and time (2-6 h) on inhibition efficiency was studied using Response Surface Methodology [82]. The results reveal that *almond* leaves extract effectively inhibits the corrosion rate of aluminum immersed in the acidic medium. The concentration of 0.38 g/l, the temperature of 36°C, and the time of 5 h gave the optimum conditions to validate the predicted values. The experimental value of 97.9% agreed closely with that obtained from the predicted model. This study revealed that *Almond* fruit extract could be recommended as a low-cost and good inhibitor for acid corrosion of Aluminum. *Artemisia herba-alba essential* oil extract was investigated as a green inhibitor for aluminum corrosion by Hechiche et al. in 1 M HCl solution [83]. The chemical analysis obtained by gas chromatography and gas chromatography-mass spectrometry revealed 68 components. The inhibition efficiency was determined by weight loss measurements, potentiodynamic polarization, electrochemical impedance spectroscopy, and scanning electron microscope. The results revealed an increase in inhibition efficiency by a maximum of 92% by increasing the oil concentration to 3 g/L at 333 K. The oil compounds adsorb by physisorption, follow Langmuir adsorption isotherm, and act as mixed-type inhibitors. The EIS results confirmed the adsorption mechanism process and the SEM observations. Ouchelli et al. tested the corrosion inhibition of volatile extract of *Artemisia Herba-Alba* for pure aluminum in 1M HCl using weight loss measurement and potentiodynamic polarization, open circuit potential, and electrochemical impedance spectroscopy techniques [84]. The results revealed that the inhibition effectiveness was dose-dependent on the oil concentration. The maximum inhibition was determined to be 94.3% for an optimal concentration of 0.8 g/L. The polarization studies showed that *Artemisia Herba-Alba* essential oil acts as a mixed type inhibitor without changing the hydrogen evolution mechanism. SEM studies revealed improvements in Al surface in the presence of *Artemisia Herba-Alba* essential oil, which confirms the formation of an adsorbed and protective barrier of *Artemisia Herba-Alba* essential oil molecules.

The inhibition efficiency of different concentrations of *Azwain* seed extract on aluminum corrosion in 0.5 M HCl solution was investigated by Anabarasi and Divya [85] using the weight-loss method, electrochemical, and surface analysis techniques. The weight-loss method showed an increase in inhibition efficiency up to a particular concentration of *Azwain* seed extract and then a decrease on the same with increasing inhibitor concentration. A polarization study indicated that *Azwain* seed extract affects both anodic and cathodic reactions. Alternative current impedance spectra showed that a protective film is formed on the metal surface. Adsorption of the extract on the aluminum surface was found to obey Langmuir and Frumkin's adsorption isotherms. The corrosion of aluminum using *Polygonatum odaratum* [86] extract was studied using weight loss measurements, potentiodynamic polarization, electrochemical impedance spectroscopy, scanning electron microscopy (SEM), and electron dispersive X-ray spectroscopy (EDX) techniques. The inhibition efficiency of aluminum in the presence of *Polygonatum odaratum* plant extract at 303-333 ± 1K in 1 M HCl was determined with the weight loss technique. The experimental results reveal that the inhibition efficiency of *Polygonatum odaratum* plant extract increased with increased concentration of the inhibitor and decreased temperature.

Ademoh determined the inhibitive effect of *Watermelon* oil on the corrosion of aluminum in H_2SO_4 solutions using the weight loss method [87]. Each aluminum sample in solution with 0.0, 0.5, 1.0, 1.5, and 2% *Watermelon* seed oil inhibitor showed increased cumulative weight losses with the increase of the exposure time during 0-240 hours. Results showed that the H_2SO_4 solution gradually corroded the aluminum during exposure. The corrosion mechanism is based on electrolytic cell formation in which the H_2SO_4 solution acted as an electrolyte, and different points in the aluminum samples with varied electrical potentials acted as tiny anodes and cathodes for a complete galvanic cell circuit. As a result, H_2SO_4 was ionized into H^+ and $SO4^{-2}$ in the solution to activate the release of Al^{+3} at these tiny aluminum anodes. These anions and cations reacted to the precipitate aluminum hydroxides, sulfides, sulfates, and sulfites with hydrogen bubbles and water that and water that resulted in gradual dissolution and weight loss of samples. The cumulative weight loss after 0, 48, 96, 144, 192, and 240 hours of exposure showed a pattern of decreased weight loss with increased inhibitor concentration from 0.0 to 0.5% *Watermelon* seed oil. It increased with increased oil concentration from 0.5% through 1.0 to 1.5% of *Watermelon* seed oil and then decreased with increased inhibitor concentration from 1.5% to 2.0% *Watermelon* seed oil. The *Watermelon* seed oil is rich in Omega 6 and 9 fatty acids that are known to impart a good penetration property to the oil. This assisted the oil adsorption despite the low surface adhesion coefficient of aluminum. The fatty acids adsorbed shielded the metal surface from $SO4^{-2}$ attack and reduced the corrosion.

The corrosion inhibition of aluminum in different HCl concentrations such as 0.20 M, 0.40 M, 0.60 M, and 0.80 M in the presence of ethanol extract of *Anogeissus Leiocarpus* at room temperature was studied by Ayuba and Mustapha using thermometric technique [88]. The effect of the addition of halides (KCl, KBr, KI) is also investigated. The percentage inhibition efficiency increased with an increase in the concentration of ethanol extract of *Anogeissus Leiocarpus.* The addition of the halides to the plant extract increased the inhibition efficiency to a maximum of 95.18% with KI at 0.6g/L concentration. The decrease in inhibition of efficiency was found to be in the order $I^- > Br^- > Cl^-$. This order clearly shows that the radii and the electronegativity of halide play a significant role in the adsorption process. During aluminum corrosion in HCl solution without the plant extracts, the concentration of KCl and KBr increases the corrosion rate of aluminum, while for KI, a reverse case was observed.

Prabhu and Rao studied the corrosion inhibition characteristics of aqueous extract of seeds of *Coriandrum sativum* L. as an eco-friendly green inhibitor for corrosion control of aluminum in 1.0 M phosphoric acid solution [89]. The researchers used potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) techniques at different temperatures. According to Tafel polarization results in inhibition efficiency of the extract increased with an increase in concentration. However, these values decreased with an increase in temperature. The maximum inhibition efficiency was determined as 71.51% with the potentiodynamic polarization method for 500 ppm *Coriandrum sativum* L extract at 30°C. This value was found at 72.75% with the electrochemical impedance spectroscopy method.

The adsorption of the extract on the Al surface obeyed Langmuir adsorption isotherm. The extract acts as a mixed inhibitor by inhibiting both cathodic and anodic reactions to the same extent. The energy of the activation value suggests that the extract undergoes physical adsorption on the surface of the aluminum. The surface morphology of aluminum and the absence and presence of *Coriandrum sativum* L extract in 1.0M phosphoric acid solution were studied by scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy. Nyjime and Ayuba revealed the correlation between the quantum chemical parameters and inhibition efficiency of *Coriandrum sativum* L. compounds using DFT/B3LYP calculations [90]. The inhibition efficiency of the inhibitors was closely related to the quantum chemical parameters, E_{HOMO}, E_{LUMO}, ΔE, electron density, and dipole moment. All inhibitors have a considerable tendency for the protonation process to be a downhill exothermic reaction. All values calculated adsorption energies, E ads are negative, which means that adsorption could occur spontaneously. Molecular dynamic simulations of the inhibition were performed to study the adsorption behavior of the inhibition of the aluminum [110] surface. It was observed that the adsorption occurs mainly through the alone pair of electrons of the heteroatoms and p- electron of the *Coriandrum sativum* L. compounds.

Nnaji et al. revealed the inhibitive effects of *Cashew nut testa tannin* for aluminum corrosion in different hydrochloric acid solutions such as 0.1 M, 0.5 M, and 2.0 M using gravimetric, thermometric, and UV/visible spectroscopic techniques [91]. *Cashew nut testa tannin* inhibition was by adsorption on aluminum following Temkin isotherm in 0.1 M HCl and Langmuir isotherm in 0.5 M and 2.0 M HCl at 303 K. Physical adsorption on aluminum has been proposed in studied HCl solutions. It was determined that *Cashew nut testa tannin* is a cathodic inhibitor. The study investigated the correlation between computed molecular parameters and inhibitive properties of inhibitor and adsorption sites on its components. Calculated quantum chemical parameters, namely: E_{HOMO} (highest occupied molecular energy), E_{LUMO} (lowest unoccupied molecular orbital energy), energy gap (ΔG), and dipole moment (μ), suggest that *Cashew nut testa tannin* is a soft inhibitor and its component inhibited aluminum corrosion in protonated forms. Calculated Mulliken charges implicated some electron-rich sites, namely: the aromatic and conjugated C=C, C=O, and O-H as adsorption sites on the inhibitor molecules. The proposed kinetic model showed a complex reaction mechanism, parallel reactions for aluminum corrosion inhibition by inhibitor.

Considering the literature, it is seen that additional to the above mentiones references; many studies are showing that plant extracts are used as corrosion inhibitors to reduce aluminum corrosion in acidic environments. These plant extracts are shown in Table 1.

TABLE 1. Various plant extracts as corrosion inhibitors for aluminum in acidic media

Extract	Medium	Methods	Type of adsorption	Maximum inhibition efficiency (η,%)	Ref
Eromomastax polysperma	0.5 M HCl	weight loss, thermometric methods	Langmuir	81.70	[92]
Analygin	0.5 M HCl	weight loss, potentiodynamic polarization, electrochemical impedance spectroscopy (EIS), atomic force methods (AFM), computational studies	Langmuir	92.00	[93]
Areca flower	0.5 M HCl	weight loss, Tafel plot, electrochemical impedance spectroscopy (EIS), electron microscopy (SEM)	Langmuir	94.44	[94]
Areca palm leaves	0.5 M HCl	mass loss, potentiodynamic polarization, AC impedance spectroscopy, electron microscopy (SEM)	Langmuir	89.49	[95]
ethanol extract of *Ruellia Tuberosel*	0.5 M HCl	weight loss, potentiodynamic polarization, EIS, energy-dispersive X-ray spectroscopy, FT-IR, SEM	Langmuir	82.77	[96]
Gassipium Hirsum L.	1.0 M HCl	weight loss	Langmuir	92.00	[97]
Aloe plant	0.5-1.5 M HCl	electrochemical polarization	Freundlich	83.65	[98]
Asparagus racemosus	1.0 M HCl	weight loss, quantum chemical techniques, SEM	Langmuir	80.54	[99]
Ocimum gratissimum	1.0 M HCl	gravimetric	Temkin	95.65	[100]
Conocarpus Erectus	1.0 M HCl	weight loss, potentiodynamic polarization, EIS, SEM	Temkin	91.10	[101]
Pawpaw leaves	1.0 M HCl	gravimetric, potentiodynamic polarization, SEM, FT-IR, RSM	Langmuir	80.58	[102]
Cerumium rubrum	1.0 M HCl	weight loss, hydrogen evolution, electrochemical impedance spectroscopy (EIS), EFM, ATR-FT-IR, and UV visible AFM	Langmuir	86.00	[103]
Saffron	2.0 M HCl	weight loss, electrochemical polarization, SEM	Temkin	84.60	[104]
Black mullbery	2.0 M HCl	weight loss, electrochemical polarization, SEM	Langmuir	92.95	[105]
Melia azedorach	2.0 M HCl	weight loss,	Langmuir	86.02	[106]

Extract	Medium	Methods	Type of adsorption	Maximum inhibition efficiency (η,%)	Ref
		potentiodynamic polarization, EIS			
Prasopis laevigata	0.5 M H_2SO_4	weight loss, potentiodynamic polarization, EIS	Langmuir	93.63	[107]
Bread fruits peels	0.5 M H_2SO_4	weight loss,	Langmuir	85.30	[108]
Hemerocallis fulva	1.0 M H_2SO_4	weight loss, potentiodynamic polarization, SEM-EDX	Langmuir	89.00	[109]
Tecoma	1.0 M H_2SO_4	weight loss, potentiodynamic polarization, EIS, (EFM)	Langmuir	90.20	[110]
Persea Americana	1.0 M H_2SO_4	gravimetric	Langmuir Temkin	78.90	[111]
Millet Starch added KI	2.0 M H_2SO_4	Gravimetric, quantum chemical (DFT)	Langmuir	88.99 93.27	[112]
Agarose	1.0 M HCl 0.5 M H_2SO_4 0.5 M H_3PO_4	weight loss, Tafel extrapolation, EIS, SEM, theoretical study	Temkin	81.00	[113]
Terminalia chebula Ritz	0.5 M H_3PO_4 1.0 M H_3PO_4 2.0 M H_3PO_4	potentiodynamic polarization, FT-IR, SEM, EDXS, AFM	Langmuir	83.24 79.11 78.04	[114]
Cordia myxa	1.0 M H_3PO_4	weight loss, AFM, FT-IR	Langmuir	90.95	[115]
Cydonia Vulgaris	1.0 M H_3PO_4	weight loss	Langmuir	95.51	[116]

The effect of *Commelina diffusa* leaf extract on aluminum corrosion in 2 M HCl solution was studied by Abakedi and Ekpo using weight loss, thermometric, and hydrogen evolution methods [117]. The inhibition efficiency increased with an increase in extract concentration and temperature. The maximum inhibition efficiency was found at 97.70% when the inhibitor concentration was 4.0 g/l at 40°C. Chemical adsorption is proposed to account for the adsorption of the extract onto the aluminum surface, based on an increase in the inhibition efficiency with an increase in temperature coupled with a decrease in the activation energy (E_a) in the extract relative to the blank. The adsorption of *Commelina diffusa* leaf extract onto aluminum surface conformed to the modified Langmuir adsorption isotherm. Due to the negative values of adsorption free energies ($\Delta G°_{ads}$), the adsorption of the extract is spontaneous.

Guar gum was investigated as a possible eco-friendly corrosion inhibitor for pure aluminum by Palumbu et al. in a 1M HCl solution at different temperatures and immersion times using gravimetric and electrochemical techniques [118]. The results showed that *Guar Gum* was a good corrosion inhibitor for pure aluminum in the studied environment. The inhibition efficiency of *Guar Gum* increased with increasing inhibitor concentration and immersion time but decreased with increasing temperature. Polarisation measurements revealed that *Guar Gum* was a mixed type of inhibitor with a higher influence on the cathodic reaction. The adsorption behavior of the investigated inhibitor was found to obey the Temkin adsorption isotherm, and the calculated values of the standard free adsorption energy indicate mixed-type adsorption, with the physical adsorption being more dominant. The associated activation energy (E_a) and the heat of adsorption supported the physical adsorption nature of the inhibitor. Fourier-Transform Infrared Spectroscopy (FT-IR) and Raman/SERS were used to explain the adsorption interaction between the inhibitor with the surface of the metal. The results suggested that most inhibition action of *Guar Gum* is due to its adsorption of the metal surface via H-bond formation.

Umoren et al. determined the corrosion inhibition for aluminum in H_2SO_4 using *Gum Arabic* at 30-60°C using weight loss and thermometric techniques [119]. The effect of the addition of halides (KCl, KBr, and KI) was also investigated. *Gum arabic* acted as an inhibitor for aluminum in H_2SO_4, and its inhibition efficiency (%) increased with the concentration of *Gum arabic*. The addition of halides increased the inhibition efficiency significantly increase in temperature caused a decrease in inhibition efficiency, The increase in inhibition efficiency and degree of surface coverage (ϴ) was found to order I^-> Br^-> Cl^- suggesting that the radii and electronegativity of the halide ions play a significant role in the adsorption process. The synergism parameter (S) is found to be greater than unity, indicating that the enhanced inhibition efficiency is only due to synergism. *Gum arabic* obeyed the Langmuir, Temkin and Freundlich adsorption isotherms.

Eddy et al. proved that *Ficus thonningii* gum can be used as an adsorption inhibitor for the corrosion of aluminum in H_2SO_4 [120]. For this purpose, gravimetric and hydrogen evaluation studies have been done. From the pattern of variation of inhibition efficiency with temperature, either of the two mechanisms of adsorption (physical and chemical adsorption) is feasible. However, the determined results point toward physical adsorption as distinct from chemical adsorption, where the inhibition efficiency is expected to increase with increasing temperature. Adsorption and inhibitive properties of *Ficus sycomorus* gum on the corrosion of aluminum illustrated by Ju'o et al. in 0.1 M HCl medium at different temperatures of 303 and 333K using the gravimetric method [121]. The inhibition efficiencies of *Ficus sycomorus* gum increase with the increase in its concentration and decrease with an increase in temperature and period of immersion time. Values of activation energy of the inhibited corrosion reaction of aluminum were greater than the value obtained for uninhibited corrosion reaction. Thermodynamic consideration revealed that adsorption of the inhibitor on the aluminum surface was exothermic, spontaneous, and was through the mechanism of physical adsorption. The adsorption characteristic of the inhibitor was best described by the Langmuir adsorption isotherm. The anti-corrosive effect of *Pachylobus eduli*s exudate gum in combination with halide ions (Cl^-, Br^-, and I^-) for aluminum corrosion in HCl was published by Umoren et al. [122]. The authors studied the temperature range of 30-60°C using the weight loss method. The inhibition efficiency increased with an increase in the concentration of the *Pachylobus edulis* exudate *gum* but decreased with an increase in temperature and synergistically increased to a considerable extent on the addition of the halide ions. The increase in inhibition efficiency (I%) and surface coverage (Θ) in the presence of halides were found to be in the order $I^- > Br^- > F^-$, which indicates that the radii, as well as electronegativy of the halide ions, play a significant role in the adsorption process. The values of the synergism parameter (S_1) obtained for the halides are more remarkable than unity suggesting that the enhanced inhibition efficiency of the *Pachylobus edulis* caused by the addition of the halide ions is only due to the synergistic effect. The adsorption of halides *Pachylobus edulis* exudate -halide mixtures fit into the Temkin isotherm model.

Eddy et al. determined the corrosion inhibition properties of *Ficus Benjamin* gum by weight loss analysis [123]. GCMS and FT-IR analysis methods were also used. It is found that the corrosion rate of Al in the presence of an inhibitor decreases with an increase in temperature while its inhibition efficiency increases with an increase in temperature. According to experimental findings, *Ficus Benjamin* gum acted as an adsorption inhibitor that favors the chemical adsorption mechanism. Adsorption could be explained by the Langmuir adsorption model.

Sharma et al. tested *Solanum surrattence* on corrosion behavior of aluminum in various concentrations of hydrochloric acid media [124]. The inhibitive properties of plant extract of *Solanum surrattence* in acetone, petroleum ether, and methanol has been determined using weight loss and thermometric methods. Both weight loss and thermometric determinations have shown that the inhibition efficiency increases with increasing inhibitor concentration over the range of 0.12%-0.60% and with an increasing acid concentration within the range of 0.1 N to 5 N HCl solutions. This inhibitor inhibits the Al corrosion 97.60% at its maximum value at 25°C. At a higher temperature, the inhibition efficiency decreases. It is revealed that the adsorption of compounds on aluminum obeyed Langmuir adsorption isotherm.

Abochi et al. reported the inhibitive effect of *Alcapha wilkesiane* on aluminum corrosion in a 1 M hydrochloric acid medium [125]. Corrosion rates were determined using the linear polarization technique. Tafel slopes (βa and βc) were also determined by Tafel polarization measurements. The authors studied at room temperature. It has been determined that inhibition efficiencies increase in the presence of *Alcapha wilkesiane.*

Corrosion inhibition of aluminum using *Carica papaya* in 1 M H_2SO_4 and 1 MH_3PO_4 was investigated by Karuga [126]. The researcher studied under different temperatures such as 30°C, 40°C, and 50°C and concentrations (from 20-100 v/v%). Gravimetric analysis, i.e., the weight loss method as the primary method, was used for the investigation. Electrochemical experiments have also been in the study. Characterization was also determined using scanning electron microscopy (SEM) and Fourier Transform Infrared spectroscopy (FT-IR). *Carica papaya* leaves extract was found to have a maximum inhibition efficiency of 71.67% and 56.02% in H_2SO_4 and H_3PO_4, respectively, at the optimal concentration range from 60 to 80 v/v% in both acids used. The adsorption of the inhibitor onto the metal surface seems to obey Langmuir adsorption isotherm by having a high correlation coefficient of approximately equal to 1. Results from this investigation show that *Cariya papaya* extract can be used to develop a commercialized natural corrosion inhibitor. Inhibition of aluminum corrosion using *Carica papaya* leaves extract in 1.0 M H_2SO_4 was investigated by Kasuga et al. using gravimetric analysis at various concentrations and temperatures 303 K, 313 K, and 323 K [127]. Characterization was done using a scanning electron microscope (SEM) and Fourier Transform Infrared (FT-IR) spectroscopy. Results show that inhibiting ability of the extract was due to its adsorption onto the metal surface through the Langmuir adsorption isotherm. Some thermodynamic parameters such as Gibbs energy, heats of adsorption, and kinetic parameters such as activation energy and entropy of activation were also determined. The difference in thermodynamic and kinetic parameters in the absence and presence of the extract proved its adsorption. The difference in SEM images of the aluminum surface by the one with inhibitor to be smoother than the surface without it is also proof of the inhibitor adsorption as well as activeness. The investigation of ethanol extract of *Carica papaya* as an inhibitor for the corrosion of aluminum in solutions of HCl was investigated by Eddy et al. using gravimetric, gasometric, potentiodynamic polarization, and quantum chemical methods [128]. The synergistic combination of various concentrations of the inhibitor with 0.6 M of KBr, KI, and KCl enhanced the inhibition efficiency to the following ranges 75.44 to 87.41%, 50.20 to 71.89%, and 77.44 to 88.73%, respectively. The adsorptive and inhibitive properties of the extract are strongly dependent on the extract concentration, temperature, and period of contact of the aluminum metal with the solution of HCl. The adsorption of the extract on the aluminum surface was exothermic, spontaneous, and occurred with increasing entropy changes. Freundlich and Temkin's isotherms were most suitable for explaining the extract's adsorption behavior. In quantum chemical calculations, the sites for electrophilic, nucleophilic, and radical attacks have been established for the respective active molecules using the Fukui function, Huckel charges, and Local softness.

The corrosion inhibition of aluminum in 1N HCl in the presence of C*arica papaya* and *Azadirachta indica* was studied by Ebenso et al. [129]. The researchers studied at 30-40°C using the weight loss, thermometric, and hydrogen evaluation techniques. In studied all conditions, the inhibition efficiency (I%) increased with the increased concentration of the extracts and with increased temperature. It is determined that *Carica papaya* is a better inhibitor at 30°C, whereas *Azadirachta indica* is better at 40°C. Both *Carica papaya* and *Azadirachta indica* obeyed Freundlich, Temkin, and Flory-Huggins adsorption isotherms at all concentrations studied at 40°C. In the study, adsorption characteristics such as activation energy E_a and adsorption free energy ΔG_{ads} were also calculated.

Nithya et al. indicated the inhibition properties of *Beetroot* (Betanin) for aluminum corrosion in an aqueous solution at pH 3 [130]. For this purpose, the researchers applied the mass loss method, potentiodynamic polarization, and electrochemical impedance spectroscopy techniques. The aluminum corrosion behavior in the absence and presence of different concentrations of *Beetroot* extract was investigated under the influence of various experimental conditions. According to experimental results, *Beetroot* extract is a good eco-friendly inhibitor for aluminum in an aqueous solution at pH 3. The polarization curves showed that extract behaves mainly as an anodic inhibitor. The synergistic effect findings between *Beetroot* extract and Zn^{+2}. Alternative current impedance spectra reveal that a protective film formed on the aluminum surface, and FT-IR spectra reveal that the protective film consists of Al^{+3}- betanin complex and $Zn(OH)_2$. The results of the mass-loss study show that the formulation consisting of 2mL of *Beetroot* extract a 25 ppm of Zn^{+2} has 98% inhibition efficiency in controlling aluminum corrosion in an aqueous solution at pH 3. When the solution, 25 ppm Zn^{+2} and 2mL of extract at pH 3, is prepared, there is the formulation of Zn^{+2} - betanin complex in the solution. When aluminum is immersed in the solution, the Zn^{+2} -betanin complex diffuses from the bulk of the solution towards the aluminum surface Zn^{+2}-betanin + Al^{+3} Al^{+3}-betanin + Zn^{+2}. The released Zn^{+2} combines with OH^- to form $Zn(OH)_2$ on the cathodic sites. Thus, the protective film consists of Al^{+3}-betanin complex and $Zn(OH)_2$. The results obtained from mass loss, polarization, and impedance measurements are in good agreement.

Investigation of exudates of *Eucalyptus citriodora* as corrosion inhibitors of aluminum was investigated by Ezeukonkwo et al. using the weight loss technique. In various concentrations of hydrochloric acid (0.1, 0.2, 0.3, 0.4, and 0.5 M) solutions, it was found that the presence of exudates of *Eucalyptus citriodora* inhibited aluminum corrosion at 30°C [131]. Free energy of adsorption ($\Delta G°_{ads}$) values are negative and suggest spontaneous inhibitor adsorption on aluminum. Temkin adsorption isotherm fitted-best obtained adsorption data for tannis of *Eucalyptus citriodora* on aluminum in various HCl solutions. Lawan et al. revealed the inhibition properties of *Eucalyptus camaldulensis* for aluminum in different HCl media by applying weight loss measurement and kinetic study [132]. The concentrations of HCl were selected from 1 M to 4 M. The studied temperatures are 30°C, 40°C, and 50°C. In the study, inhibitor concentrations were determined as 0.5 M, 1.0 M, 1.5 M, and 2.0 M. For the same temperature, as increased inhibitor concentration, corrosion rate decreases. For the same inhibitor concentration, corrosion rate decreases with temperature, i.e., inhibition property increases. There was an increase in corrosion rate with variation from 1.0 to 4.0 M at all studied temperatures, while the least corrosion rate was observed in 1.0 M concentration. The optimum value of inhibitor efficiency was obtained at a concentration of 2.0 (% w/v). The highest inhibitor efficiency of 94% was obtained at 50°C. The difference between the trends of inhibitor efficiency of *Eucalyptus camaldulensis* concentration presently studied intensely suggests that the mechanism of adsorption of the inhibitor on the aluminum sample surface is predominantly by chemical adsorption. The variation of free energy with inhibitor concentration from 30°C to 50°C showed that obtained the highest free energy was in inhibitor concentration of 2.0 (% w/v) at 30°C, while the most negligible value was observed at 0.5 (%w/v) at 50°C.

The inhibitive properties of various concentrations (0.913-0.522 g/l) of *Coriander* seed extract molecules for the pure aluminum surface in a 1 M HCl medium were performed by Shah et al. using weight loss and electrochemical impedance techniques [133]. Results from gravimetric tests showed an increment in inhibition efficiency with an increase in inhibitor concentration. The maximum inhibition efficiency of *Coriander* seed was found to be 82.49% with weight loss and 81.401% by impedance spectroscopy techniques at 35°C. Extract molecules followed Langmuir adsorption isotherm, and it was observed from its free energy value that the inhibitor molecules might be physisorbed over the metal surface. The result from impedance measurements displays that the constant phase element decreases, and the charge transfer resistance value was raised with an escalation in the concentration of inhibitor. A Quantum chemical study was performed using density functional theory (DFT) to elucidate the inhibitory activity of individual molecules present in the extract.

Ladha et al. revealed the inhibition property of *Fennel* seed extract as a corrosion inhibitor for pure aluminum in 1.0 M hydrochloric acid using gravimetric, galvanostatic polarization, and electrochemical impedance techniques [134]. The results from gravimetric techniques reveal an increase in inhibition efficiency with an increment in extract concentration. The galvanostatic polarization result revealed that the mode of inhibition was the mixed type with a predominance of cathodic inhibition. The results from impedance measurements showed that with an increase in the concentration of inhibitor, charge transfer resistance increases while double-layer capacitance value was deduced, indicating adsorption of phytochemical constituent present in the extract at metal/solution interphase. The quantum chemical calculation facilitates the judgment that E-anethole pursues the highest activity as a corrosion inhibitor compared with other molecules present in the extract. Prajapati et al. determined aluminum corrosion inhibition in HCl solution by *Fennel (Foeniculum Vulgare Mill)* seeds extract as a green inhibitor using weight loss, temperature effect, and kinetic study methods [135]. HCl acid was used as corrosive media having a concentration of 0.75, 1.0, and 1.25 M. When inhibitor concentration increases, corrosion rate decreases while percentage inhibition efficiency increases, but corrosion rate increases with the increase in temperature. The maximum inhibition efficiency of *Fennel* seed extract was found at 92.01% at 1.2 g/L inhibitor concentration in 0.75 M HCl solution. Mechanism of inhibition efficiency was also investigated by calculating the thermodynamic and activation parameters such as adsorption free energy (ΔG_{ads}), adsorption heat (Q_a), activation energy (E_a), adsorption enthalpy (ΔH_{ads}), and adsorption entropy (ΔS_{ads}). According to these parameters, physisorption occurs. The Langmuir adsorption isotherm can best explain the physisorption of the extract. The negative free energy of adsorption ΔG_{ads} indicates strong and spontaneous adsorption of the *Fennel* seed extract on the aluminum surface.

Melilotus officinalis extract was investigated as a green corrosion inhibitor for aluminum in 1 M HCl solution by Fouda et al. using weight loss, hydrogen evolution, potentiodynamic polarization, electrochemical impedance spectroscopy

(EIS), and electrochemical frequency modulation (EFM) techniques [136]. Surface morphology was investigated using a scanning electron microscope (SEM). The effect of temperature on corrosion behavior with the addition of different inhibitor concentrations was studied in the temperature range of 25°C -45°C by weight loss technique. The results obtained from the weight loss technique showed that the inhibiting action increases with the increase in temperature. The *Melilotus officinalis* extract' inhibits the corrosion by getting adsorbed on the metal surface following the Temkin adsorption isotherm. The inhibition efficiencies determined by all techniques are in reasonably good agreement.

Dubey et al. studied the corrosion inhibition efficiency of leaves extract of *Withania somnifera* on aluminum in HCl solution at two temperatures, i.e., 308 K and 313 K [137]. The efficiency of inhibitor increases with increasing concentration of inhibitor as well as with that of HCl. The study reveals that the inhibitor prevents excellently at its concentrations of 0.8% for 2 N HCl, where its maximum efficiency is 99.28%. In another study, corrosion inhibitive effects of *Withania Somnifera* (*Ashwagandha*) were studied by Dubey in different concentrations (0.5 N, 1.0 N, and 2.0 N HCl) of HCl [138]. Studies have shown that both leaves and root extract showed similar trends for different concentrations of acid as well as those inhibitors. Studies were carried out at two different temperatures (303 K and 318 K) to extract of leaves and roots of the plant. Leaves extract of *Withania Somnifera* has been found to be a more effective corrosion inhibitor at a lower temperature. The maximum inhibition efficiency was found at 99.28% for leaves extract for 0.8 M inhibitor concentration in 2 N HCl at 303 K. It can be concluded from the studies that *Withania Somnifera* is a better corrosion inhibitor at 303 K than 318 K, and leaves extract is more efficient than root extract.

Green coffee bean extract as a green corrosion inhibitor for aluminum in artificial acid rain medium was published by Binyehmed et al. [139]. The authors studied at pH 4.3 (H_2SO_4+HNO_3), and electrochemical measurement (Tafel polarization) was applied to determine inhibition parameters. The results indicated that the *green coffee bean* extract could be used to reduce aluminum corrosion in the tested medium. The inhibition efficiency reached a maximum value of 8.0 g/L of 84.4%, 97.4%, and 98.1% for 300, 313, and 323 K temperatures. These findings proved that the Langmuir isotherm was the best model for the adsorption of aluminum metal. The effects of *Lactuca sativa* (*Lactuca*) extracts on the aluminum corrosion in 1 M HCl were investigated as eco-friendly corrosion inhibitors by Al-Saeedi et al. using potentiodynamic polarization and weight loss studies [140]. Surface morphology was tested by scanning electron microscopy (SEM). The results show that inhibition efficiencies increased with an increase in extract concentrations.

Maximum inhibition effectiveness was found at 98.6%. The adsorption of the inhibitor extract on the aluminum surface is spontaneous and obeys the Langmuir isotherm. The results obtained from polarization measurements show that the *Lactuca sativa* (*Lactuca*) extract acts as a mixed-type inhibitor with predominant anodic effectiveness.
The inhibition effect of Lemon Balm (Melissa Officinalis) leaves extract on aluminum corrosion using the weight loss method was investigated by Ogbonda and Vitalis [141]. The study was carried out at different concentrations of the extract and temperatures. The inhibition efficiency of the extract was found to increase as the concentration of extract increased but decreased as the temperature increased. The maximum inhibition efficiency was obtained at 96.57% in 50% v/v extract concentration and 30°C temperature. A physical adsorption mechanism occurred for this extract, and the Langmuir adsorption isotherm was found as the best adsorption model.

E. Ogbonda investigated the corrosion inhibition of aluminum using ethanol extract of *Vinegar* (*Rhustyphina*) leaf in 1 M HCl using the weight loss method at 30°C, 40°C, and 50°C temperatures [142]. The inhibition efficiency was found to have increased with an increase in the concentration of the extract. The maximum inhibition efficiency of 92% was obtained at 50% v/v inhibitor concentration. The reduction in corrosion rate was due to the adsorption of the extract on the metal surface, as revealed by Langmuir's adsorption isotherm plot. The corrosion inhibition efficacy of alcoholic extracts of stem, leaves, and fruits of *Cordia dichotoma* towards hydrochloric acid for aluminum has been studied by Khandelwal et al. using mass loss and thermometric methods [143]. It has been observed that at constant acid concentration, the inhibition efficiency of all the extracts increases with inhibitor concentration, while at constant inhibitor concentration, the inhibition efficiency decreases with the increase in acid concentration. It has also been observed that the inhibition efficacy decreases with the increase in temperature.

Aluminum corrosion inhibition in 1.0 M hydrochloric acid solution by *Caffeine* has been indicated by Beda et al. using mass loss technique and quantum chemical calculations based on density functional theory (DFT) [144]. The inhibition efficiency increases with the concentration of *caffeine* but decreases with a temperature rise. *The caffeine* molecule shows the highest inhibition efficiency of 74% at 10^{-2} M at T= 303 K. The experimental data were fitted with the Langmuir isotherm model of El-Awady. However, it was found that the adsorption parameters suit well the isotherm of El-Awady, which was chosen as the appropriate isotherm. To distinguish between physisorption and chemisorption, the Dubinin-Radushkevivh adsorption model was used. DFT study gave further insight into the mechanism of the inhibiting action of *Caffeine*. The negative sign of $\Delta G°_{ads}$ suggests a spontaneous adsorption process. The values of change in adsorption-free enthalpy $\Delta G°_{ads}$ and that of the activation energy E_a indicate the presence of both physisorption and chemisorption. The quantum chemical calculations are in good agreement with experimental results.

Dawodu and Sodiya revealed corrosion inhibition of aluminum by leaf extract *Telfaira occidentalis* using the gasometric technique at 28°C [145]. The protected aluminum surface by the extract against acid attack was observed in the SEM analysis. The phytochemicals in the extract displayed high corrosion inhibition efficiency. The corrosion inhibition mechanism followed the Langmuir adsorption isotherm. This suggests the extracted constituent chemisorbed on the aluminum surface, forming a protective film minimizing direct contact with the corrodent. The inhibitory effect of *Solenostemon monostachyus* leaf extract on aluminum corrosion in HCl solution was studied by Abakedi using weight loss, thermometric, and hydrogen evolution methods [146]. Inhibitory efficiency was found to increase with an increase in extract concentration and temperature. A chemical adsorption mechanism has been proposed for the adsorption of the leaf extract onto the aluminum surface. Thermometric parameters showed that the adsorption of the extract onto the metal surface was endothermic and spontaneous. The adsorption of *Solenostemon monostachyus* leaf extract on Al's surface obeyed the Freundlich adsorption isotherm.

Oluseyi et al. published the inhibition properties of the crude extract of *Azadirachta indicia* for aluminum in a 1.85 M hydrochloric acid environment by gasometric technique [147]. The aluminum samples were immersed in test solutions of uninhibited 1.85 M HCl and those containing extract concentrations of 10%, 20%, 30%, 40%, and 50% at room temperature. It was observed that *Azadiracha indicia* extract retarded the acid-induced corrosion of aluminum, and the volume of hydrogen gas evolved reduced with increasing extract concentration. The adsorption studies revealed that Langmuir isotherm is the best model for adsorption of *Azadirachta indicia* on the aluminum surface. Ekeke et al. studied *Azadirachta indica* seed (*neem* seed) extract as an anti-corrosion agent for aluminum in a 0.5 M hydrochloric acid medium [148]. The extract and corrosion products were analyzed using Fourier transform infrared spectrometer (FT-IR). Thermometric and potentiodynamic polarization methods were applied in the study. Inhibitor concentrations were selected from 0.2g/l to 1.0 g/l, while time variation was from 1 hour to 5 hours. It was revealed that stretched C-H and C=C functional groups were predominantly responsible for the corrosion inhibition process.The highest inhibition efficiency of 88.68% was obtained for the thermometric method and 86.36% for the potentiodynamic polarization method at an inhibitor concentration of 1.0 g/l.The extract is a mixed-type inhibitor that can control both anodic and cathodic corrosion. Arab et al. investigated the synergistic action caused by iodide ions on the corrosion inhibition of aluminum in 0.5 M HCl in the presence of *Azadirachta indica* plant extract [149]. The researchers used potentiodynamic polarization and impedance techniques. Azadirachta indica extract was found to inhibit aluminum corrosion in 0.5 M HCl. The inhibition efficiency increases with the increase in the extract concentration until 24% v/v of the extract; then, inhibition efficiency is decreased with a further increase in the extract concentration. The adsorption of the extract in the studied concentration is found to obey Freundlich adsorption isotherm. The addition of iodide ions enhances the inhibition efficiency to a considerable extent. The increase in inhibition efficiency values in the presence of a fixed concentration of iodide ions indicates that *Azadirachta indica* extract forms an insoluble complex at lower extract concentrations by undergoing joint adsorption. The synergism parameter (S) was defined and calculated from surface coverage values. This parameter in the case of *Azadirachta indica* extract was found to be more than unity, indicating that the addition of iodide ions caused the enhanced inhibition efficiency. The value of the synergism parameter is more remarkable than unity, showing that the corrosion inhibition brought out by extract and I^- ions in combination is synergistic in nature. The adsorption of the extract followed the Temkin isotherm model for both polarization and impedance methods. In another study, Ekeke et al. examined *Azadirachta indica* seed extract (*neem seed*) as an anti-corrosion agent for aluminum in a 0.5 M HCl medium using the gravimetric (weight loss) methods [150]. The inhibition efficiency was optimized by application of Response Surface Morphology (RSM) using Design Expert Software 11. Inhibitor concentration was determined from 0.2g/l to 1.0g/l; the temperature range was selected from 303 K to 343 K. Time was applied from 1 hour to 5 hours. *Azadirachta indica* seed extract increased as the inhibitor concentration increased, with the highest inhibition efficiency recorded at the highest inhibitor concentration of 1 g/l. The adsorption of the extract on the aluminum surface adhered to the mechanism of physical adsorption. The isotherms were perfectly fitted by the Langmuir isotherm. A quadratic model described the inhibition efficiency as a function of inhibitor concentration, temperature, and immersion time, with inhibitor concentration having a more significant effect. The optimum inhibition efficiency of 84.763% was obtained at an inhibitor concentration of 0.901 g/l, a temperature of 317.521 K, and an immersion time of 3.898 hours. Desai indicated the effect of *Azadirachta* *indica* (*Neem*) leaves ark's on the aluminum corrosion in 0.4, 0.5, and 0.6 M HCl and elucidates the mechanism of the inhibition system [151]. Gravimetric and galvanostatic polarization methods were used to determine the protective effect of the extract for aluminum corrosion in HCl. According to the experimental results, inhibition efficiency increases with increased extract concentration. At the highest concentration of 1.29%, the inhibition efficiency increased to a maximum value of 91%. Polarization study shows that the inhibitor behaves as a mixed type of inhibitor. The adsorption study promotes that Langmuir isotherm best described the metal surface interaction with the *Azadirachta indica* leaves ark's to adsorb to the metal surface at all concentrations.

Ladha et al. determined the corrosion inhibitory activity of *Trigonellafoenum graecum* (*fenugreek*) extracts using gravimetric, galvanostatic polarization, and electrochemical impedance spectroscopy (EIS) techniques [152]. The results from the gravimetric method show that inhibition efficiency increases with an increase in inhibitor concentration. However, inhibition efficiencies decrease with an increase in temperature. Al samples were corroded at higher temperatures indicating their ineffectiveness at a higher temperature. In galvanostatic polarization, measurements did not show a significant change in the corrosion potential. Therefore, it can be accepted that *Trigonellafoenum graecum* is a mixed-type inhibitor. However, the results also show that the cathodic Tafel slope is higher than the anodic Tafel slope showing the predominance of cathodic inhibition. The results show that the presence of *Trigonellafoenum graecum* reduces the corrosion rate of Al due to the action of phytochemical constituents such as *Trigonelline* and *Vitexin* present in it, as obtained from Liquid Chromatography-Mass spectrometry (LC-MS) analysis. The maximum inhibition efficiency was found at 82.83% from weight loss measurement at 0.939 g/l (exposure period 60 minutes). This value was obtained at 83.78% in the same extract concentration from the polarization technique. From the EIS technique, it was determined as 86.536% in the same extract concentration.EIS measurement results indicate that the constant phase element value decreases and charge transfer resistance increases with an increase in the concentration of inhibition. The reason for such behavior is due to the adsorption of inhibitor molecules over the metal/solution interface. The experimental findings obtained were found to obey Langmuir adsorption isotherm.

The inhibitive property of the *Trigonella foenum graecum* seeds on the corrosion of aluminum has been investigated by Sharma [153]. The weight-loss method experimented with 0.5 N HCl. The results showed that *Trigonella foenum graecum* inhibited corrosion of aluminum very effectively. The inhibition efficiency (IE%)

was found to be highest at 88% for the concentration of inhibitor 1.056 g/L at immersion time of 48 hours at 303 ±1 K. FT-IR spectroscopy, and optical micrography techniques further studied the inhibitor's adsorptive behavior. FT-IR spectra showed most of the organic molecules present in the inhibitor and some complexes formed between şthe inhibitor and metal surface. Optical micrographs confirm the formation of the protective film over the aluminum surface by the inhibitor used.

Ennouri et al. showed the corrosion inhibition properties of the *Trigonellafoenum-graecum* L extract in a 1 M HCl medium using electrochemical polarization experiments and electrochemical impedance spectroscopy (EIS) method [154]. In this study, three organic solvents, pentane, dichloromethane, and ethanol, were tested. The temperature effect on the potentiodynamic curves showed that the decrease of aluminum corrosion in the presence of the extract in a 1 M HCl medium acted by a mixed process with an anodic tendency for both extracts with ethanol and pentane; however,, the extract with dichloromethane showed a cathodic tendency. Experiments were carried out at many temperatures such as 10°C, 20°C, 30°C, and 40°C. The temperature effect on the corrosion of aluminum indicated that the inhibition efficiency of the *Trigonella–graecum* L extract decreases with an increase in temperature. The efficiency increases with the increase of the concentration of inhibitor to reach 84.41% for the extract with ethanol, 86.6% for the extract with dichloromethane, and 75.77% for the extract with pentane at 1400 ppm. Three extracts are characterized by physical adsorption of *Trigonella–graecum* L on the Al surface. There is also spontaneous adsorption because of the negative values of adsorption free energy.

The inhibition properties of *Tender arecanut seed* (TAS) extract were determined by Raghavendra and Bhat by applying five different temperatures such as 303, 308, 313, 318, and 323 K [155]. The researchers used gravimetric, polarization, and impedance techniques. Findings obtained from gravimetric measurements show that the inhibitory effect of TAS extract was enhanced by increasing its concentrations. The inhibition of aluminum corrosion in the presence of an inhibitor could be attributed to the adsorption of extract constituents onto the aluminum surface. Adsorption of constituents of TAS extract onto the surface of aluminum obeys the Langmuir adsorption isotherm. According to polarization curves, TAS extract is a mixed type of inhibitor, influencing both anodic and cathodic reactions by simply blocking active aluminum metal sites. Electrochemical impedance studies show that TAS extract molecules adsorbed onto the aluminum surface and modified the aluminum – electrolyte interface.

Surface analysis by atomic force microscopy (AFM) illustrated the inhibitory action of TAS extract on aluminum in 0.5 M HCl. The same researchers proved the inhibition property of *Dry arecanut* seed (DAS) extract on aluminum metal in 0.5 M HCl medium through weight loss, electrochemical, and probe techniques [156]. Weight loss studies exhibited the anticorrosive effect of DAS extract constituents on the aluminum metal surface, and protection efficiency increased with an increase in the DAS extract concentration. The inhibited effect was afforded by adsorption of the DAS extract components, which was approximated by proper Langmuir isotherm fit. Tafel plots suggested a mixed-mode action of the extract molecules on aluminum surfaces. AC impedance spectroscopy results suggested that constituents of DAS extract were adsorbed on the aluminum surface and modified the metal/acid solution interface. The activation energy and other thermodynamic parameters were determined to corroborate the experimental results and provide adequate insight into the aluminum corrosion inhibition mechanism. Surface analysis rationalized via atomic force microscopy (AFM) technique manifested the absence of corrosion products and topographic modifications on the aluminum surface. The amorphous/crystalline nature of inhibitor molecules adsorbed onto the aluminum surface was indicated by X-ray diffraction techniques. Protection efficiency values obtained by all techniques were compiled which each other. Raghavendra and Bhat, in their other study, investigated the corrosion inhibition behavior of ethyl acetate extract from *Mature arecanut* seed (EEMAS) and water extract from *Mature arecanut* seed (WEMAS) on aluminum in 0.5 M hydrochloric acid medium by applying gravimetric (weight loss), electrochemical (Tafel plot and AC impedance) and surface probe (SEM) and (AFM) techniques [157]. From the gravimetric technique, it was observed that the superior inhibition property was ensured at the concentration of 12 gl^{-1} of plant extracts. This value was determined to be 94.44 for WEMAS, while it was found to be 88.80% for EEMAS at 303 K temperature. The same trend was observed in all studied temperatures like 308, 313, 318, and 323 K. However, the protection efficiencies of both extracts decrease with increasing temperature. The chemical or physical nature of the film formed by plant extracts (both EEMAS and WEMAS) was further inspected based on the kinetic and thermodynamic parameters. According to Tafel studies, the current corrosion value decreases appreciably with an increase in the plant product concentration, which indicates a reduction in the corrosion rate. The AC impedance spectroscopy technique showed an increase in the charge transfer resistance values with the addition of plant extract constituents to the corrosive medium. Surface characterization of target metals by scanning electron microscopy (SEM) and atomic force microscopy (AFM) techniques as a function of contact time in 0.5 M HCl medium noticeably gives about the protective role of plant extracts on the aluminum surface. The order of protection efficiency obtained from all techniques was found to be WEMAS > EEMAS. Raghavendra and Bhat revealed the inhibition effect of extracts of *Yellow color ripe arecanut husk* on the inhibition of aluminum corrosion in 0.5 M HCl medium by weight loss and electrochemical techniques [158]. The protection efficiency of the inhibitor varied with inhibitor concentration. The protective action of the *Yellow color ripe arecanut husk* extract increases with the increase in its amounts in 0.5 M HCl solution. The Langmuir isotherm model shows that *Yellow color ripe arecanut husk* extract inhibits aluminum corrosion in 0.5 M HCl solution by adsorption mechanism. Tafel curves proved that *Yellow color ripe arecanut husk* extract is a mixed type inhibitor. Results of Nyquist curves confirmed that adsorption of the extract species led to an enhancement in charge transfer resistance values and a decrease in values of double-layer capacitance. In the study, scanning electron microscopy and atomic force microscopy techniques were used to examine the aluminum surface morphology without and with the extract. The effect of *Red arecanut* seed extract on the corrosion of aluminum in a 0.5 M hydrochloric acid environment was published by Raghavendra and Bhat using weight loss, electrochemical (Tafel plot and impedance spectroscopy), scanning electron microscopy (SEM), and atomic force microscopy (AFM) studies [159]. The efficiency of the *Red arecanut* seed extract increases with increasing its amount in 0.5 M HCl solution. The maximum inhibition efficiencies were determined as 83.33% from weight loss measurements, while these values were found 87.93% and 91.34% from Tafel plots and impedance spectroscopy methods, respectively. Slight desorption of *Red arecanut* seed extract constituents on the aluminum surface was observed with increasing solution temperature from 303 to 323 K, indicating the physical adsorption process. Langmuir's adsorption model is well fitted for studying the system. The electrochemical results (both Tafel and AC impedance spectroscopy study) confirm the adsorption of *Red arecanut* seed extract at the aluminum -HCl system interface. Obtained from by SEM and AFM technique shows the smooth aluminum surface topography in the presence of plant product the inhibitory action of *Red arecanut* seed extract.

Ugi et al. investigated corrosion inhibition in the presence of alkaloid and non-alkaloid extracts of *Cnidoscolus aconitifolius* in 1 M HCl using the weight loss and hydrogen evolution techniques at 303, 313, and 333 K [160]. The results obtained revealed that the inhibition efficiency decreased with an increase in temperature. Inhibition occurred through adsorption of the alkaloid and non-alkaloid extracts molecules on the aluminum surface. Some thermodynamic parameters such as activation energies, enthalpies, and entropies of the dissolution process and the free energies and enthalpies for the adsorption process were determined. The adsorption process followed a mechanism of physical adsorption, and the adsorption obeyed Langmuir adsorption isotherm.

Investigation of the adsorptive and inhibitive effect of extracts of *Alstonia boonei* on aluminum corrosion in 1.0 M sulphuric acid was reported by Ituen et al. [161]. Gravimetric and gasometric measurements were used to determine the inhibition characteristics of *Alstonia boonei* extract. The temperature range was selected from 303 to 333 K and extract concentrations were 0.3, 0.4 and 0.5 g/L. Corrosion rate decreased with an increase in extract concentration. The decrease in inhibition efficiency occurs with an increase in temperature. Adsorption behavior was best approximated by the Freundlich adsorption model. The adsorption of the extract onto the metal surface was spontaneous and exothermic.

The inhibitive effect of *Acanthus montanus* leaves extract on aluminum corrosion in hydrochloric acid solutions was studied by Udom et al. using the weight loss technique [162]. It was found that the leaf extract retards the acid-induced corrosion of aluminum. Inhibition efficiencies increase with the increase in inhibitor concentration but decrease with an increase in temperature. The thermodynamic study of the inhibition process yielded negative values of free energy of adsorption, indicating spontaneity of *Acanthus montanus* extract adsorption of the aluminum surface. Adsorption was found to obey Temkin isotherm.

The corrosion inhibition and adsorption of ethanol extracts of *Psidium guajava* seeds for aluminum corrosion in 0.5 N HCl solutions were published by Y.C. Sharma and S.Sharma [163]. The authors investigated using weight loss, FT-IR spectroscopy, and SEM analysis techniques. The analysis of the results showed that the inhibition efficiency increased with an increase in the inhibitor concentration but decreased with an increase in the temperature. Analysis of FT-IR results showed that the inhibition mechanism was explained by the adsorption process through the functional groups present in the extract. The physical adsorption mechanism of the inhibition process was confirmed by the data obtained, and the Langmuir model was best fitted with the results. The calculated activation energy values also confirmed a physical adsorption mechanism. The SEM images of the aluminum samples show that the aluminum metal was protected in the presence of the extract.

Rajendran applied pharmacological and corrosion inhibition studies of flavonoids obtained from *Nerum oleander* and *Tecona stans* [164]. Corrosion inhibition studies on aluminum in acidic medium 2 M HCl at 30±1°C were investigated by weight loss and polarization studies. The corrosion rate decreased considerably, or the% inhibition of corrosion increased in the presence of compounds obtained from the plants. This is attributed to the fact that the active principle constituents of the natural products from the protective film on the metal surface coordinate with the metal ion through O, S, and N atoms of the functional groups present in the active principle constituents. When the active principle constituents are extracted with acids or organic solvents or with water, usually a mixture of inhibitors present in the plant extract may show a synergistic effect. The extracts obtained from the two flowers *Nerium oleander* and *Tecoma stans,* inhibit the corrosion of aluminum. Hence, it is concluded that these plant extracts can be used as a corrosion inhibitor for aluminum in 2 M HCl.

Majeha et al. investigated the protective effect of *Solanum melongena L.* leaf extract on the corrosion of aluminum in 0.5 M H_2SO_4 by using the gravimetric method [165]. According to the experimental findings for a given concentration of *Solanum melongena L.* leaf extract in 0.5 M H_2SO_4, the inhibition efficiency decreases with exposure time. Nevertheless, the inhibition efficiency of the extract tends to increase exponentially with extract concentration for a given exposure time. Further analysis of experimental data showed a modified form of the Langmuir adsorption isotherm, and the value and sign of the Gibbs free energy of adsorption ($\Delta G°_{ads}$) revealed that the inhibitor molecules had been spontaneously adsorbed onto the aluminum surface through a physical adsorption mechanism.

Coco nucifera L water as a corrosion inhibitor for acid corrosion of aluminum in 0.5 mol/L HCl has been studied by Abiola and Tobun using the weight loss technique [166]. It was shown that the corrosion rate decreased with increasing *Coco nucifera* L water concentration in HCl solutions, and the inhibition efficiencies increased with increasing *Coco nucifera* L water concentration. The maximum protection efficiency was determined in 0.5 M HCl solution with 93% at 7.5% (v/v) concentration. Inhibition is due to the adsorption of the inhibitor onto the metal surface, and the adsorption obeys the Langmuir adsorption isotherm. The value of adsorption free energy ΔG°_{ads} was negative, and this sign indicates the spontaneity of the adsorption process.

Halambek and Berkovic investigated the inhibition effect of *Anethum graveolens* L essential oil on the corrosion of aluminum in 1 M HCl solutions by weight loss, potentiodynamic polarization, and electrochemical impedance spectroscopy (EIS) methods [167]. It was shown that inhibition efficiency increased with increasing oil concentration. However, it decreased with increased temperature. The maximum inhibition efficiencies were determined 96.9% and 98.0% in 300 ppm inhibitor concentration at 298 K from weight loss and polarization results, respectively. The results of potentiodynamic measurements revealed that *Anethum graveolens* L oil is a cathodic inhibitor for aluminum corrosion in a 1 M HCl medium. EIS measurements showed that the increase of *Anethum graveolens* L oil concentration increases the charge transfer resistance, while at a concentration higher than 100 ppm of *Anethum graveolens* L oil inductive loop in the Nyquist plots completely disappeared, which indicates prevention of local corrosion. The adsorption of *Anethum graveolens* L essential oil obeys Langmuir adsorption isotherm.

Corrosion inhibition efficiencies of *Holy basil* on Al in HCl solution were studied by Kumpawat et al. by weight loss and thermometric methods in the absence and presence of stem extract of three different varieties of *Holy basil* viz.*ocimum basilicum* (E_B), *ocimum canum* (E_c) and *ocimum santcum* (E_S) [168]. HCl concentrations were selected as 0.5 N, 1.0 N, 2.0 N, and 3.0 N. Inhibition efficiency increases with the increasing concentration of stem extract and decreases with increases in acid strength. Results showed good corrosion inhibitors; among them, E_B is the most effective. The maximum inhibition efficiency was found 97.09% in 0.5 N HCl with 0.6% stem extract. Both methods (weight loss and thermometric) show the same trends in corrosion efficiency, and the results are in good agreement with each other.

Corrosion inhibition of aluminum in 1 M HCl solution using 30% (v/v)ethanol solution of *Lavandula angustifolia L* oil was investigated by Halambek et al. [169]. The researchers studied potentiodynamic polarization and EIS methods. It was shown that *Lavender* oil effectively inhibits aluminum corrosion in the concentration range from 50 to 500 ppm by volume. Potentiodynamic polarization findings showed 90.2% maximum inhibition efficiency in 500 ppm inhibitor concentration at 298 K. This value was found 86.2% in the same conditions. Polarization curves indicated that *Lavender* oil acts as a cathodic inhibitor for aluminum in HCl solution. EIS results confirmed that active compounds present in this oil have the ability to form a protective layer on the aluminum surface.

The inhibition ability of *Nephelium lappaceum* peel extract as a corrosion inhibitor of aluminum in 0.1 M HCl solutions were published by Norzila et al. [170] from the gravimetric and thermometric analysis. The authors showed that the value of the inhibition efficiency was proportional to increasing inhibitor concentration and inversely proportional to the temperature. The maximum inhibition efficiency was obtained 92.42% in 0.50 gl^{-1} inhibitor concentration at 30°C. The activation energy values increased with increasing extracted inhibitor concentration. This case confirms that a physical adsorption mechanism has occurred on the aluminum surface. SEM findings also confirmed there is adsorption of *Nephelium lappaceum* peel extract molecules onto the aluminum surface.

Akın et al. determined the inhibition action of *Juglans regia* L. for corrosion of aluminum in 1 M HCl solution by using gravimetric (weight loss), potentiodynamic polarization, and electrochemical impedance spectroscopy methods [171]. An increase in inhibition efficiency was shown with the increased concentration of inhibitor *Juglans regia* extract, both in water and ethyl acetate solutions. The maximum inhibition efficiency was found at 88.8% in a water solvent. For each experiment, the water showed better efficiency as a solvent than ethyl acetate solution. The effect of immersion time (2-8 h) was discussed, and the adsorption mechanism was fitted with the Langmuir isotherm. FT-IR analysis also supports the adsorption of inhibitor molecules in the study. The inhibition efficiency of *Juglans regia* extract can be explained by its antioxidant effect. All these findings illustrate that *Juglans regia* extract can be used as an effective eco-friendly corrosion inhibitor for aluminum in 1 M HCl. The inhibition properties of *Juglans regia* extract as an eco-friendly inhibitor for the aluminum metal in a 2 M HCl medium were published by Fouda et al. [172]. The authors used mass loss, gasometric methods, potentiodynamic polarization, electrochemical impedance spectroscopy, and electrochemical frequency modulation methods. Polarization curves indicated that extract acts as a mixed-type inhibitor. Inhibition efficiency values of *Juglans regia* vary depending on concentration and temperature. The impact of electrochemical impedance spectroscopy displayed the expansion in the polarization resistance (R_p) and decline in the double-layer capacitance (C_{dl} The adsorption of the extract on the outside of aluminum from the damaging corrosive medium obeys Langmuir adsorption isotherm. The AFM examination of the Al surface showed that the concentrate avoided dissolution by adsorption on the surface. FT-IR outcomes demonstrated the presence of many functional groups by which the adsorption process occurs. XPS studies affirmed the arrangement of the defensive layer of the extract on the Al surface.

Corrosion inhibition ability of *Borassus flabellifer coir dust* extracted by water (BFDWE) and methanol (BFDME) against aluminum was reported by Nathiya et al. in 1 M H_2SO_4 at 303-333K [173]. The authors examined using electrochemical, non-electrochemical, and microstructure analysis. The experimental results depicted that corrosion inhibition efficiency increases with the addition of inhibitor concentration, and it adversely decreases as a function of temperature. The highest inhibition efficiencies of ~66.8% and ~ 52% were determined by BFDME and

BFDWE, respectively, for inhibitor concentrations of 0.4 g/l. Furthermore, adsorption of molecules, presence in two extracts on active sites of the aluminum surface was physisorption and obeyed Langmuir adsorption isotherm. Potentiodynamic results indicated that two extracts perform as mixed-type inhibitors with notable cathodic nature. The surface morphology study by scanning electron microscope (SEM) further confirmed the existence of passive layers of BFDME and BFDWE molecules on top of the aluminum surface, thus promoting anti-corrosion.

Illicium verum extract was investigated as a corrosion inhibition of aluminum in the presence of a 1 M HCl medium by Ladha et al. using gravimetric and impedance techniques [174]. The surface characteristics of aluminum were evaluated using scanning electron microscopy-energy-dispersive X-ray spectroscopy. The maximum inhibition efficiency of 95% for an exposure period of 60 min was found at 308 K. The results obtained from gravimetric measurements were evaluated using the Langmuir adsorption isotherm, and thermodynamic data for adsorption was obtained. It was found that the inhibitor molecules were physisorbed onto the Al surface. Electrochemical impedance spectroscopy results showed the presence of adsorbed inhibitor layer Al surface in 1 M HCl solution. The interaction between the chemical constituents or inhibitor molecules and the metal surface was evaluated using Monte Carlo simulation. The determination of electron density on the inhibitor molecules was performed using density functional theory.

Abakedi and Moses indicated the corrosion inhibition effects of *Maesobatrya barteri* root extract for aluminum in hydrochloric acid solutions by gravimetric and thermometric methods [175]. In gravimetric experiments, *Maesobatrya barteri* root extract was used in 0.5 M HCl; in thermometric measurements, the extract was examined in 2 M HCl. According to experimental findings, the inhibition efficiency increased with an increase in root extract concentration but decreased with an increase in temperature. The maximum inhibition efficiency was determined 78.75% at 4.0 g/l at 30°C. The calculated values of (ΔH_{ads}) for aluminum corrosion in 0.5 M HCl being positive indicate the endothermic nature of the adsorption process, while the negative values of ΔG^0_{ads} obtained reveal the spontaneity of the inhibition process. Physical adsorption has been proposed for the adsorption of *Maesobatry barteri* root extract on the Al surface. Langmuir adsorption isotherm is the best fit among all adsorption isotherms.

The inhibitive performance of *Sapindus* for aluminum corrosion in the 1 M HCl solution was studied by Sharma et al., using experimental and computational techniques [176]. The inhibition efficiency of *Sapindus* was found to be proportional to its concentration in the acidic medium. The extract showed 98% of inhibition efficiency at 2000 ppm. The experimental results showed that the studied *Sapindus* adsorbs spontaneously on the Al surface and conforms to the Langmuir isotherm. SEM, AFM, and computational studies (quantum chemical and Monte Carlo) also confirmed the same and proved *Sapindus* extract is a green corrosion inhibitor.

Yanardağ et al. published the inhibitor effects of *Canabis Sativa* L extracts on the corrosion of aluminum in 0.5 M H_2SO_4 solution [177]. The authors used electrochemical methods such as the potentiodynamic current-potential method, linear polarization, and electrochemical impedance spectroscopy technique. According to the experimental findings, the inhibition efficiency *of Canabis Sativa L.extract w*as found to be around 98% at 298K. The extract acted as an anodic inhibitor, and the impedance measurements confirmed this situation.

The inhibitive and adsorption properties of aqueous extract of seeds of *Garcinia indica* extract have been shown for corrosion control of aluminum in 0.5M phosphoric acid (H_3PO_4) solution by Prabhu and Rao using potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) techniques at 30°C to 50°C [178]. The effects of inhibitor concentration on the inhibition action were studied. Polarization experiments showed that the extract acted as mixed inhibitor molecules followed by chemical adsorption on the surface of the aluminum. The adsorption of the extract on the metal surface obeyed Langmuir's adsorption isotherm. The inhibiting performance of *Garcinia indica Choisy* extract was shown by Prabhu et al. via electrochemical impedance spectroscopy (EIS) technique and by using response surface methodology (RSM) in the design of the experiment [179]. The surface analysis was carried out using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) to affirm the adsorption inhibitor on the surface of the metal. In the study, the influence of three parameters such as extract concentration, acid concentration, and temperature are considered on the inhibition efficiency of Al in acid. The optimum settings for the studied parameters were found to be at 50°C, extract concentration ($0.5 gL^{-1}$), and acid concentration (0.5 M) to achieve the maximum inhibition efficiency of 86.19%.

Sargassum latifolium extract was tested as a new extract for the protection of Al corrosion in 1M HCl by Fouda et al. [180]. The researchers used chemical and electrochemical methods. *Sargassum latifolium* was extracted, tested, and its high inhibition efficiency with the addition of $1x10^{-2}$M KI at 298 K for 300 ppm in 1 M hydrochloric acid was studied. The adsorption mechanism agreed with the Temkin isotherm from the weight loss method. This extract behaves as a mixed-type inhibitor. The thermodynamic parameters were determined. Moreover, the attenuated total reflectance-Fourier Transform Infrared Spectroscopy (FT-IR) and atomic force microscopy (AFM)were performed for the Al surface analyses. In addition, the extract has also demonstrated a satisfying biological activity against bacterial growth.

The experimental studies of the corrosion inhibition properties of *Strichnos spinosa* L. were carried out by Ayuba and Abdullateef both using weight loss and Fourier transform infrared spectroscopy (FT-IR) and theoretical methods [181]. The analyses of the experimental results indicate that the extract of *Strichnos spinosa* L. extracts decreased the corrosion rate of aluminum in 0.9 M HCl in the order: 0.2g/l < 0.4 g/ l < 0.6g/l respectively from 303-323 K. The inhibition efficiency decreased with an increase in temperature, and maximum inhibition was found to be 84.7%. FT-IR results showed that the inhibition mechanism is physical through the functional groups present in the extract. Adsorption of the extract obeys the Freundlich isotherm. Results from quantum chemical parameters and molecular dynamic simulation prove the adsorption/binding strength of the concerned inhibitor molecules on aluminum surface follows the order Ursolic acid > Betulinic acid >Erythiodiol. The computed adsorption/binding energy values (E_{ads}) for various isolated compounds from the plant indicate the adsorption process to be physisorption. The values of molecular quantum chemical parameters such as E_{HOMO}, E_{LUMO}, the energy gap ($\Delta E= E_{HOMO}-E_{LUMO}$), ionization potential, electron affinity, absolute hardness, global softness, absolute electronegativities, and a fraction of electron transferred were calculated. The magnitude of the obtained adsorption energy (i.e., less than 100 kcal/mol) confirms the strong physisorption of the molecules onto the Al surface. In another study, the same researchers investigated the corrosion inhibition potentials of *Strichnos spinosa* L extract on aluminum in 0.3 M hydrochloric acid solution by using weight loss (WL), linear polarization resistance (LPR), scanning electron microscopy (SEM), and Fourier transform infrared spectroscopy (FT-IR) methods [182]. The effect of extract concentration (0.2g/l to 0.6g/l) and temperatures (303 K-323 K) on corrosion and corrosion inhibition of aluminum was investigated. The inhibition efficiency values increased with increasing extract concentration. The maximum inhibition efficiency of the extract was determined at 98.04% for the weight loss method and 88.48% for the linear polarization resistance (LPR) method at 303 K temperature. LPR studies revealed that *Strichnos spinosa* L extracts performed as a mixed type of inhibitor. The adsorption process followed the Freundlich isotherm. The negative value of ΔG_{ads}, FT-IR and SEM results predicted the adsorption process to be spontaneous and proceed through physisorption.

Ezeugo et al. examined the inhibitive capacity of *Akuamma seed* extract in 1.0 M HCl of aluminum using response surface methodology (RSM), gravimetric (weight loss), potentiodynamic polarization, and electrochemical impedance spectroscopy techniques [183]. The optimal inhibition efficiency of 72.6% was obtained at an optimum inhibition concentration of 1.2g/l, the temperature of 304.19 K, and maximized time of 11.53 hours. The interaction between the adsorbed extract molecules and the aluminum surface is a physical process. The extract protects aluminum against pitting corrosion. The degree of protection increases with increased extract concentrations. The maximum inhibition efficiency was obtained as 89.2% in 1000 gL^{-1} extract concentration. From the gravimetric method, maximum inhibition efficiency of 73.60% was obtained with an inhibition concentration of 1.2g/l. The extract inhibited both cathodic and anodic reactions and acted as a mixed-type inhibitor. The adsorption process of *Akuamma seed* extract on the surface of aluminum is spontaneous, stable, and follows the Langmuir adsorption isotherm.

Abakedi showed the inhibitive action of *Microdesmis puberula* leaf extract on aluminum corrosion in 2 M hydrochloric acid solution by both thermometric and hydrogen evolution methods [184]. The inhibition efficiency increased with an increase in *Microdesmis puberula* leaf extract concentration but decreased with an increase in the temperature. For example, according to hydrogen evolution data, the maximum inhibition efficiency was found as 88.67% at 303 K temperature, while this value was determined to be 80.13% at 323 K. The adsorption of *Microdesmis puberula* extract onto the aluminum surface best fits the modified Langmuir adsorption isotherm. The negative values of adsorption free energy, $\Delta G°_{ads}$, reflect the spontaneity of the corrosion inhibition process. A physical adsorption mechanism (physisorption) has been proposed for the adsorption of *Microdesmis puberula* leaf extract onto the aluminum surface.

The corrosion of aluminum in a 2 M HCl medium in the absence and presence of *Tussilago Farfara* extract was determined by Fouda and Haleem [185]. The researchers applied Tafel polarization, electrochemical impedance spectroscopy (EIS), electrochemical frequency modulation (EFM), gasometry, and mass loss methods. All methods illustrated that the inhibitive effect rises with increasing the *Tussilago Farfara* extract amounts and reduces with elevating the temperature from 25°C to 45°C (physical adsorption). The protection effect of the extract indicated the blocking of the Al surface by adsorption of its components through the reacted atoms contained in its molecules. The adsorption of the extract is in accordance with the Langmuir isotherm. Impedance results indicated that the dissolution of Al is monitored by charge transfer mode at all concentrations of the extract. FT-IR check of the extract and dissolution product demonstrated the functional groups that have coordinated with Al^{+3}. Varied surface examinations like XPS and AFM were checked to affirm the presence of the defensive film on the Al surface.

Prajapati and Vashi investigated the inhibition of the corrosion of aluminum in hydrochloric acid solutions by the leaves extract of *Ocimum sanctum* (Tulsi) using weight loss, potentiodynamic polarization, and electrochemical impedance spectroscopy (EIS) techniques [186]. HCl acid concentrations were selected as 0.75 M, 1.0 M, and 1.25 M. At constant acid concentration, as inhibitor concentration increases, corrosion rate decreases while inhibition efficiency increases. Corrosion rate increases with the increase in acid concentration and temperature. The leaf extract of *Ocimum sanctum* showed maximum inhibition efficiency of 85.17% at an optimum concentration of 1.2 g/L. The values of activation energy (E_a) obtained in the presence of the extract were higher compared to the blank acid solutions. The values of free energy of adsorption ($\Delta G°_{ads}$) were negative, which reveals the spontaneous adsorption of the *Ocimum sanctum* onto the Al surface. In addition, the heat of adsorption (Q_{ads}), enthalpy of adsorption ($\Delta H°$ ads), and entropy of adsorption were also calculated. The results showed that *Ocimum sanctum* molecules adsorbed on the metal surface, and it obeys Langmuir adsorption isotherm. Polarization curves indicated that *Ocimum sanctum* acts as a mixed-type inhibitor.

The inhibition effect of *Dennettia tripelata* (*pepper fruit*) extract on aluminum corrosion in a 0.5 M H_2SO_4 medium was investigated by Erebugha et al [187]. Phytochemical analysis was carried out using quantitative and qualitative methods, respectively. Fourier transform–infrared (FT-IR) spectroscopy was applied to determine the functional groups of phytochemicals. Weight loss and electrochemical techniques were used for the corrosion study within a temperature range of 303 K to 323 K.Weight loss studies revealed that inhibition efficiency increased from 62.3% to 95.5% with increasing concentrations of extracts from 200mg/l to 1000mg/l. According to EIS findings, the maximum inhibition efficiency was determined as 98.1% in 1000mg/l extract concentration. Polarization curve measurements showed it to be a mixed-type inhibitor. The electrochemical impedance study showed that corrosion inhibition of aluminum in a 0.5 m sulfuric acid medium takes place through an adsorption process that occurs on the aluminum surface. The adsorption of *Dennettia tripelata* extract in an H_2SO_4 environment on aluminum obeys Langmuir adsorption isotherm. SEM findings confirm the existence of a film coating layer on the metal-solution interface.

The *Rice straw* extract was used as an eco-friendly green inhibitor to prevent Al corrosion in 2 M HCl by Fouda et al. [188]. Mass loss, potentiodynamic polarization (PP), electrochemical impedance spectroscopy (EIS), electrochemical frequency modulation (EFM) techniques and surface checks were used to indicate the importance of the extract to the corrosion inhibition process of Al in 2M HCl. From mass loss experiments, it can be understood that the inhibition efficacy reached 96.8% after 3 hours at 25°C. According to polarization curves, *Rice straw* extract is a mixed type inhibitor that retards the al dissolution and hydrogen evolution reactions. From EIS results, the reduction of the double-layer by raising the concentration of the extract was observed, and on the other hand, the charge transfer resistance is increased. By raising the concentration of *Rice straw* extract, the effectiveness of the inhibitor increases due to its adsorption on the Al surface. Adsorption of the extract molecules complies with the Langmuir and Flory-Huggins isotherms, and the adsorption was mixed, but mainly physical adsorption. The activation energy of the *Rice straw* extract has higher values than in its absence and increases with increasing the extract concentration. The results obtained from the free energy of adsorption (ΔG°_{ads}) and the enthalpy of the adsorption (ΔH_{ads}), are spontaneous and exothermic in nature.

The corrosion inhibition property of *Gymnema sylvestre* on aluminum in a 0.5 M HCl medium has been investigated by Bashir et al. [189]. The experimental techniques such as weight loss, potentiodynamic polarization studies, and electrochemical impedance studies were applied. Quantum chemical calculations were done to confirm the experimental results. The results indicated that *Gymnema Sylvestre* extract acts as a potential corrosion inhibitor of aluminum in 0.5 M HCl medium, showing 82% inhibition efficiency at 800 ppm concentration of inhibitor. The efficiency of *Gymnema sylvestre* on the aluminum sample is seen to decrease with temperature variations and increase with increasing concentrations of the inhibitor. Potentiodynamic polarization studies revealed that *Gymnema sylvestre* is a mixed type inhibitor and an EIS study showed that *Gymnema sylvestre* forms a protective film on the aluminum surface. The experimental results illustrated that the studied *Gymnema sylvestre* adsorbs spontaneously onto the aluminum surface and conforms to the Langmuir adsorption isotherm. FT-IR spectra revealed the occurrence of chemical interactions between the inhibitor and aluminum. Quantum chemical parameters such as E_{HOMO}, E_{LUMO}, ΔE, and dipole moment (μ) values agree with experimental results.

Pimpinella Anisum extract was investigated as a corrosion inhibitor of aluminum in 1 M HCl solution by Akounach et al. [190] using linear polarization, electrochemical impedance spectroscopy (EIS), and theoretical studies such as Density Functional Theory (DFT), Monte Carlo (MC) and Molecular Dynamic (MD) simulations. Extract concentrations were selected from 0.5 g/L to 3g/L. The inhibition efficiency was found to increase with the increasing concentration of *Pimpinella Anisum* extract. Maximum inhibition efficiencies were determined as 91.04% and 89.34% in 3 g/L from polarization curves and electrochemical impedance spectroscopy methods, respectively. The electrochemical findings showed that *Pimpinella Anisum* extract behaves as a mixed type of inhibitor. However, since cathodic current densities decrease much more than those of the anodic current, the extract acts as a mixed type of inhibitor with a cathodic priority. The inhibition is due to the adsorption of the extract molecules on the aluminum surface according to the Langmuir adsorption isotherm. These results were confirmed by the electrochemical impedance plots. SEM/EDX results showed that the aluminum surface was covered with an inhibitor film. The property of this film is to hinder the reduction of H^+ ions and inhibit the dissolution of Al in 1 M HCl. DFT calculations were able to determine the adsorption centers of the extract. Moreover, the MC and MD calculations indicate the strong adsorption by the interaction of chemical constituents in the extract towards the Al surface and provide molecular facts about the geometry and adsorption energy of these inhibitors on the Al surface.

3. CONCLUSION

This review article (study) outlines the findings and data from many publications that addressed acidic environments used for evaluating plant extracts as corrosion inhibitors. Data collected in this review will be an important source for researchers to know about the plant extracts as corrosion inhibitors for metals in corrosive environments.

Acknowledgment The author would like to thank Assoc. Prof. Dr. Nurcan Acar, Ankara University, Inorganic Chemistry Department, for her assistance.

Declaration of Competing Interests The author declares that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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