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Corrosion inhibition of carbon steel by eucalyptus leaves in acidic media: An overview

ABSTRACT

This paper concerns the overview of previous studies on the corrosion and inhibition of carbon steel that is allowed to degrade in a corrosive medium by the extract of the eucalyptus plant, with an emphasis on the extract's adsorption behaviour. Many researchers have largely employed eucalyptus plant bark, oil, and leaf extracts to prevent the corrosion of mild steel in acidic environments under various temperature settings. According to the results, when the bark extract of the eucalyptus plant was added to HCl (5%) at a concentration of 900 ppm, the inhibitor's maximum efficiency was 98.2 %. The leaf extract, on the other hand, had the maximum inhibitory efficacy of 93.09 % at 600 mg/L extract concentration in the H_2SO_4 (0.5 M) medium. The extracts' potency was shown to diminish with increasing temperature. The mechanism for eucalyptus extract's protection of carbon steel from corrosion in diverse corrosive situations was largely associated with the adsorption of the extract's inhibitive components on the steel's surface to reduce the interaction between the metal and the corrosive surroundings. The majority of the reported inhibitive behaviour of the eucalyptus extract was consistent with the Langmuir adsorption isotherm model.

Keywords: *eucalyptus leaf-extract, inhibition efficiency, mild steel, Langmuir isotherm model, corrosion inhibition, carbon steel.*

1. INTRODUCTION

The breakdown of a metal as a result of its contact with its environment is known as corrosion [1]. Metal corrosion occurs as a result of its interaction with specific elements in the environment, resulting in the deterioration of metal's characteristics. This is a natural and unavoidable process [2]. Metal corrosion has several negative effects on human society's progress [3]. Alloys and metals, in particular, had shown a significant proclivity to corrode in the presence of acid. Certainly, metals are vulnerable to corrosion in acid solutions because the acid can target the metal's surface, dissolving it into its ions [4]. In addition, weldments also corrode in the presence of degrading environments [5,6].

Corrosion inhibition is one of the strategies used to reduce the impact of corrosion. In general, Corrosion inhibition is one of the strategies used to reduce the impact of corrosion. In general, corrosion inhibitors are divided into two types: inorganic and organic [7]. Organic corrosion inhibitors (such as chromium-based inhibitors) can successfully prevent metal corrosion, but they also have drawbacks. Many chemical compounds, for example, are very poisonous and will cause significant environmental harm when used [8]. The use of aqueous extracts is favoured over organic extracts in theory because aqueous extracts, being inorganic inhibitors, include comparatively polar phytochemicals that allow stronger bonding with the metallic surface than the non-polar phytochemicals of organic extracts [9].

Environmentally friendly inhibitor as a replacement for chromate-based inhibitors is a long-standing endeavour by researchers to solve environmental challenges [10]. A lot of plant extracts have previously been reported as effective for inhibiting the corrosion of carbon steel in some corrosive media [11-21]. Extracts from different parts of the eucalyptus plant have been studied

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and affirmed to be effective inhibitors to deter the corrosion of mild steel in different corrosive environments. A study to investigate the inhibitory behaviour of the oil obtained from the eucalyptus globulus leaves has been undertaken [22] It was reported that the application of the oil at 1.6 g/L gave the maximum inhibition efficiency of 89.03 % at room temperature. In addition, the inhibition efficiency was observed to reduce as the temperature increased from 298 to 338 K. The adsorption behaviour of the oil was found to be in sync with the Langmuir adsorption isotherm model. Different scholars have acknowledged the effectiveness of the eucalyptus plant extract as a natural material for inhibiting the corrosion of metal in acidic media [23,24].

This current work aims at studying recent developments on the corrosion and inhibition of carbon steel that are allowed to degrade in corrosive media by the extracts of the eucalyptus plant with the adsorption behaviour of the extract in perspective.

2. UNDERSTANDING CORROSION

Corrosion refers to the degradation process which is instigated between the metal or alloy and the exposed surrounding which invariably leads to the weakening of the physical and mechanical properties of the metal [25]. The degradation process can be in the form of an electrochemical or chemical process [26].

2.1. Electrochemical process

An electrochemical process causes corrosion. That is, corrosion often happens as a result of the attendant electrochemical half-cell processes rather than a metal reacting chemically with its surroundings directly [27]. A process in which electrons are transferred is referred to as an electrochemical reaction. The reaction also includes both oxidation and reduction. Because both processes are frequently coupled in one piece of metal, it is not always evident that corrosion is made up of a minimum of one chemical reaction and one reduction reaction [28].

2.1.1.Reactions in half a cell

When electrons only occur on one side of the reaction, the reaction is said to be a half-cell reaction. The half-cell reaction is an oxidation process if electrons are products (right side of the reaction). On the other hand, the half-cell reaction is a reduction process if electrons are reactants (on the left-hand side of the reaction) [27]. A half reaction (also known as a half-cell reaction) is the oxidation or reduction reaction portion of a redox reaction in chemistry [29].

2.1.2.What happens at the anodic half-cell

An anodic reaction results in metal loss, viz:

$$Fe(s) = Fe^{2+}(aq) + 2e^- \qquad (1)$$

The reaction can be possible if there is a rise in the species' oxidation number, and the process produces electrons [27]. Figure 1 presents a graphical representation of these concepts.

2.1.3.Cathodic reaction half-cell

For the reaction to be cathodic, the given species must undergo a reduction in its oxidation number.

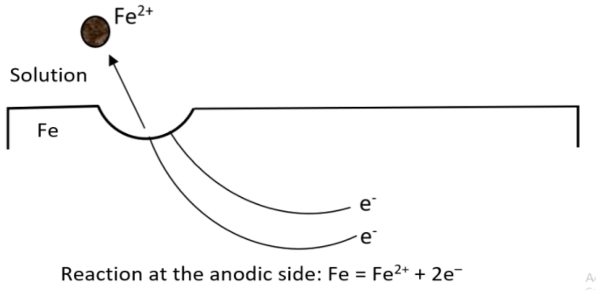

Figure 1. Schematic illustration of the dissolution of iron during anodic reaction [27]

Slika 1. Šematski prikaz rastvaranja gvožđa tokom anodne reakcije [27]

This results in the consumption of electrons at the cathodic region. A veritable instance is the decrease of 2 ions of hydrogen to give rise to one molecule of hydrogen gas [30]:

$$2H^+ (aq) + 2e^- \rightarrow H_2 (g) \qquad (2)$$

A schematic representation of this reaction is shown in Figure 2.

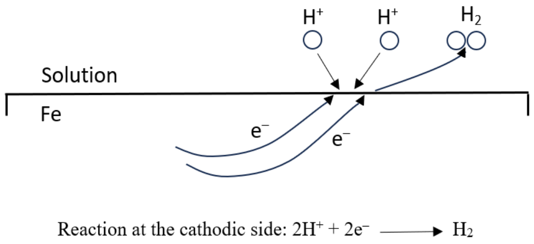

Figure 2. Schematic reaction at the cathodic region involving the evolution of hydrogen on Fe in an acid medium [27]

Slika 2. Šematska reakcija u katodnom delu koja uključuje izdvajanje vodonika na Fe u kiseloj sredini [27]

The reduction of dissolved oxygen to hydroxyl ions, which takes place in neutral or basic fluids, is another typical cathodic process [31].

$$O_2(g) + 2H_2O + 4e^- \rightarrow 4OH^-(aq) \qquad (3)$$

2.2. Electrochemical studies

2.2.1. Potentiodynamic Polarization Analysis

The Potentiodynamic Polarization Measurement (PDP) is one of the most used DC electrochemical methods used in corrosion measurements. In PDPs, a broad range of potential is given to the test electrode as a consequence of which a sufficient current is produced. Depending on the polarization direction, this causes a dominating oxidation or reduction process to occur on the metal surface. One may derive the polarization curve by presenting the potential as a function of the current density (I) (or log I) at each measured point. The metal's propensity for corrosion and rate of corrosion under the conditions present may be calculated using the polarization curve (Tafel slope) [32]. The benefit of potentiodynamic polarization measurement can be seen in the ability to detect localized corrosion, the simplicity and speed with which the corrosion rate can be calculated, as well as the effectiveness of corrosion protection. However, in many cases, to calculate the Tafel slope, we must use data that are located further away from the corrosion potential, allowing us to take into account additional reactions that could result in significant errors in the calculated slope [32,33].

2.2.2. Impedance spectroscopy for electrochemistry

The electrochemical measuring technique (EIS) uses many frequencies of AC. Over a broad frequency range (from 1 MHz to 10 kHz), it detects the electrical resistance (impedance) of the metal/solution contact. The EIS data provide for the possibility of calculating the double layer's capacitance, solution resistance, and polarization resistance (low- and high-frequency regions). The corrosion rate is frequently determined using polarization resistance [32,34].

2.2.3. Weight-loss corrosion study

Of all the corrosion monitoring systems, the Weight Loss method is the most well-known and straightforward [35]. A sample of material (the coupon) is exposed to a process environment for a predetermined amount of time before being removed for analysis. Weight loss is the fundamental measurement that may be obtained from corrosion coupons; the corrosion rate is given as the weight loss over the exposure period. As a result of the corrosion coupon technique's ease of use, it serves as the standard method of measurement in many corrosion monitoring programs. The method is incredibly adaptable since weight loss coupons may be made from any alloy that is readily available in commerce. Moreover, a range of corrosion processes employs suitable geometric shapes [35]. The corrosion rate can be quantified using the method [36]:

$$rCorr = W_{loss}/A_{exp} \times T_{exp} \qquad (4)$$

where,

$rCorr$ = rate of corrosion.

W_{loss} = difference between the initial and final weights.

A_{exp} = area of exposure.

T_{exp} = time of exposure.

The measure of the inhibition efficiency of corrosion studies can be quantified by using the relationship [37]:

$$I.Efficiency\ (\%) = ((rCorr_{un} - rCorr_{in}) / rCorr_{un}) \times 100 \qquad (5)$$

Where,

I.Efficiency (%) = Efficiency in corrosion inhibition.

$rCorr_{un}$ = corrosion rate of the blank solution.

$rCorr_{in}$ = corrosion rate of the solution wherein the inhibitor had been added.

2.3. Surface characterization method utilized in corrosion studies

2.3.1. Atomic force microscopy (AFM)

The fundamental working tenet of the AFM is the accurate detection of forces operating at very small distances between a sharp probe tip and a sample surface [38]. The contact force of a corresponding physical quantity is preserved constantly by feedback loops when the probe tip is raster-scanned across the sample surface to accomplish imaging [38]. The following elements make up an AFM (Figure 3): (i) a scanner to precisely position the sample to the probe tip in three dimensions (x, y, and z); (ii) a force sensing element and the associated detection scheme; and (iii) control electronics and a computer to (a) operate scanners and other components; (b) record, display, and save data; and (c) operate feedback loops.

According to Baykara et al. [38], a laser beam deflector is used to detect the deflections of a micro-fabricated cantilever with an integrated probe tip, while a piezoelectric scanner is used to adjust the relative tip-sample location with picometer accuracy in three dimensions. Control electronics that are in charge of tip-sample placement, data collecting, and feedback loop functioning are driven by a computer. When doing dynamic AFM, the cantilever base is stimulated with an amplitude, which causes the probe tip to oscillate [38]. Several studies have employed AFM as one of the methods to characterize the surface phenomena of metals in various corrosive environments [39].

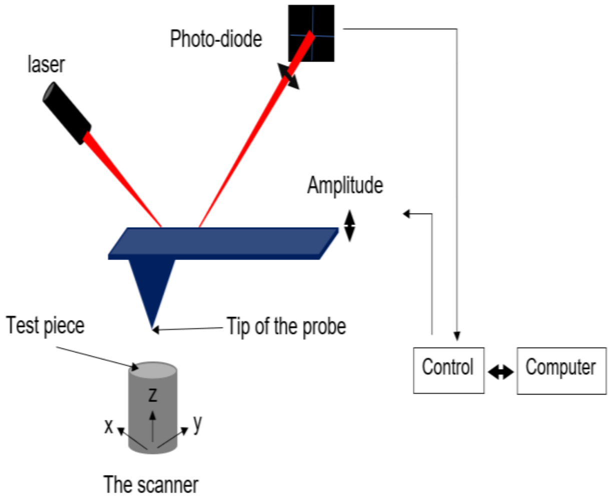

Figure 3. Diagram of a typical AFM setup [38]

Slika 3. Dijagram tipične AFM postavke [38]

2.3.2. Scanning Electron Microscopy

The scanning electron microscope (SEM) uses a focused stream of high-energy electrons to generate a variety of signals at the surface of solid objects. The signals originating from electron-sample interactions give information on the sample in addition to its external morphology (texture), chemical composition, crystalline structure, and orientation of its parts. The sample surface is typically selected for data collection, and a 2-dimensional image is produced to demonstrate the spatial variations in these parameters [40].

2.3.3. Transmission electron microscopy

To see the tiniest structures in materials, analysts utilize transmission electron microscopy (TEM). In contrast to optical microscopes, which rely on light in the visible spectrum, TEM can enlarge nanoscale structures by a factor of up to 50 million, revealing astonishing detail at the atomic scale [41]. This is because, when accelerated via a strong electromagnetic field, electrons may have a wavelength that is hundreds of orders of magnitude shorter (about 100,000 times smaller) than that of visible light, improving the resolution of a microscope by a wide margin. A high-intensity electron beam is propelled through an incredibly thin "electron transparent" material, usually less than 100 nm, to create a TEM picture. The beam of light is focused on the sample, distortions are reduced, and the resulting picture is magnified onto a phosphor screen or a specialized camera using a series of electromagnetic lenses and apertures positioned throughout the microscope's column [41].

2.4. Inhibitors that deter corrosion

There are several categories into which inhibitors might be placed. Adsorption inhibitors and film-forming inhibitors are the two primary categories.

2.4.1. Adsorption inhibitors

Adsorption inhibitors block ongoing electrochemical dissolution processes by forming a chemisorptive link with the metal surface. Chemical-type inhibitors make up the majority of organic inhibitors [27,42-43]. A schematic representation of an organic molecule with an electron pair on the nitrogen atom that is available for donation to the metal surface is shown in Figure 4 (a), for instance.

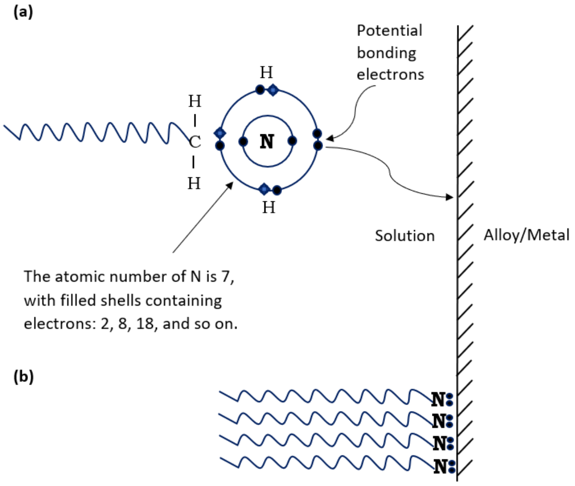

Figure 4. (a) The chemical absorption of an organic substance onto a metal surface. The symbols represent electrons from H or C atoms, whereas the solid black dots represent N atom electrons. (b) On the metal surface, a tightly packed monolayer forms [27].

Slika 4. (a) Hemijska apsorpcija organske supstance na metalnu površinu. Simboli predstavljaju elektrone iz H ili C atoma, dok pune crne tačke predstavljaju elektrone N atoma. (b) Na površini metala formira se čvrsto zbijeni monosloj [27].

Additionally, the hydrocarbon tails of the molecule are directed toward the solution and away from the interface such that an array of hydrophobic hydrocarbon tails forms on an adjacently adsorbed organic component, providing additional protection. As seen in Figure 4 (b), this hydrophobic network serves to keep water molecules and aggressive anions like Cl^- away from the metal surface [27].

2.4.2.Inhibitors of film formation

Passivating inhibitors and precipitation inhibitors are the two different manifestations of film-forming inhibitors. Passivating inhibitors work by encouraging the development of a passive coating on the surface, as suggested by their name. There are oxidizing and non-oxidizing passivating inhibitors. In the process of oxidizing another molecule, oxidizing agents undergo reduction [43]. The chromate ion is reduced to Cr_2O_3 or $Cr(OH)_3$ on the metal surface when combined with iron or steel, producing a protective mixed oxide of chromium and iron. Chromates are common oxidizing inhibitors. Since oxidizing inhibitors are often adsorbed on the metal surface before being reduced and forming the passive layer, adsorption is also crucial in the case of these substances. To create the passive film, non-oxidizing passivation like benzoates, azelates, and phosphates also initially adsorb on the surface [27].

With precipitation inhibitors, a three-dimensional barrier layer is deposited on the metal surface as a result of a precipitation interaction between the cations of the corroding metal and the inhibitor. When the salt generated between the cations of the metal and the anions of the inhibitor exceeds its solubility product, a film of this nature forms. Examples of inhibitors of the precipitation type include phosphates and silicates. According to which partial electrochemical process is impacted, inhibitors can be categorized as anodic, cathodic, or mixed inhibitors. Chromate compounds, certain phosphates, and the majority of organic molecules are all examples of anodic, cathodic, and mixed inhibitors, respectively [27].

2.4.3. Mechanism of corrosion inhibition in acidic media

The research on the adsorption of inhibitors onto the surface of the metal has found that the efficiency of an inhibitor may be determined by quantifying the amount of extract adsorbed on the metal's surface. This development can manifest in the form reduction in the rate at which the metal corrodes. According to Shreir et al. [45], the adsorbed inhibitors can be directly measured using solution depletion, and radio-tracer detection techniques.

The adsorption behaviour of an inhibitor stipulates that corrosion may be prevented within the region of the metal’s surface that is already inundated with the adsorbed inhibitive materials. In essence, the level of inhibition is commensurate with the fraction of the metal surface that is covered by the adsorbed inhibitor [45].

2.4.4. Factors that influence the adsorption of the inhibitor species on alloys and metals

It has been reported that the adsorption of the inhibitor species on alloys and metals is dependent on the metal’s surface charge, the structure of the inhibitor and the functional group, interaction of the inhibitor with water and adsorbed inhibitor species [45].

The attraction (electrostatic) interactions between the charges (ionic) on the adsorbed materials and the charge (electric) on the alloy at the solution/metal contact might cause adsorption. Whenever the potential, compared to the zero-charge potential is in the positive direction, the anions are favourably adsorbed and when it is more negative, cations are more likely to be adsorbed.

The bonding between the inhibitor species and the metal surfaces can be formed by the transfer of electrons. Transition metals are more favoured for this kind of relationship because of low energy and vacant electron orbitals. For the functional groups containing groups VI and V of the periodic table, it has been discovered that bond formation with stronger coordination (leading to stronger adsorption) occurs by these elements with descending value of electronegativity [45].

2.4.5. Interaction of the inhibitor with water and adsorbed inhibitor species

In the first instance, the metal surfaces in solutions (aqueous) are covered with adsorbed water molecules. When inhibitor molecules are adsorbed on the metal's surface, water molecules are displaced off the metal's surface. On the other hand, the increase in the adsorbed surface coverage may lead to the interaction among the adsorbed species. This reaction may either be repulsive or attractive. Repulsive reactions can exist between molecules containing charges thereby leading to poor adsorption of the inhibitor on the surface of the metal. Conversely, attractive interactions can occur between molecules that contain excessive hydrocarbons. An increase in van der Waals's attractive force between adjoining molecules makes for stronger adsorption at maximum coverage.

Through electrochemical retardation, the adsorbed inhibitor can react to form a product, which in turn can be protective. The nature of the inhibition, occasioned by the introduction of the inhibitive material into a corrosive system is referred to as primary inhibition, whereas that of the reaction product is secondary inhibition [45].

2.4.6. Inhibitors' effect on corrosion reactions

The corrosion process at the anode of an acid-containing solution involves the release of metal ions from the metal surface into the corrosive medium, whereas, at the cathode, hydrogen ions are discharged, resulting in the generation of hydrogen gas. In an acidic environment, the presence of an inhibitor may entail the decrease of one or both cathodic and anodic processes [46].

2.5. Adsorption isotherm

Several models have been established to explain the adsorption behaviour of experimental data. The current study is largely in agreement with the Langmuir adsorption isotherm model.

2.5.1.Langmuir adsorption isotherm model

The Langmuir isotherm model hinges on the assumption that under constant thermodynamic conditions, the adsorbate exhibits the behaviour of an ideal gas. In addition, the adsorption of the adsorbate is considered the interaction between an empty sorption area and the adsorbate gaseous molecule under chemical reaction conditions. The formula for the Langmuir isotherm is stated thus [47]:

$$\theta_{ads} = \frac{K_q^r \rho_r}{1+K_q^r \rho_r} \tag{6}$$

where,

θ_{ads} = fraction of material located at the adsorption area.

$\mathrm{K_q^r}$ = equilibrium constant of the adsorbate.

ρ_r = partial pressure of the adsorbate.

2.5.2. Freundlich adsorption isotherm

The Freundlich adsorption isotherm may be used to define an exponential energy distribution that surrounds a heterogeneous surface [48,49]. It gives a clear explanation of the relationship between the inhibitor concentration in a liquid that is in touch with a metal's surface and the inhibitor concentration there. The Freundlich adsorption isotherm model's mathematical formulation is as follows [48]:

$$\theta_{Cor} = K_{Frd} C_{ad}^{1/n_{it}} \tag{7}$$

where,

θ_{Cor} = The quantity of metal absorbed per gram of the adsorbent at equilibrium.

K_{Frd} = Freundlich isotherm constant (mg/g).

n_{it} = the level of absorption.

C_{ad} = equilibrium adsorbate concentration (mg/L).

2.5.3Temkin Adsorption Isotherm

The linearity in the decline of adsorption heat with surface coverage is demonstrated by Temkin's adsorption isotherm. The model is used as an example to show how the interactions between the adsorbent and adsorbate uniformly distribute binding energy. Because it explains the interactions that take place in the adsorbed layer, the Temkin adsorption model stands out from all the other models that have been previously given. In mathematics, it is expressed as [47,48]:

$$\theta_{rCorr} = B_{sp}\ InA_{Tm} + B_{Sp}\ InC_{in} \tag{8}$$

$$B_{Sorp} = \frac{RT}{b_{Tm}} \tag{9}$$

where,

θ_{rCorr} = the percentage of surface covering.

B_{Sp} = constant heat of sorption (J/mol).

A_{Tm} = Temkin isotherm equilibrium binding constant (l/g).

C_{in} = concentration of inhibitors.

R = standard gas constant (8.314J/mol/K).

T = absolute degree of heat.

b_{Tm} = Temkin's constant for isotherm.

2.6. The Eucalyptus Plant

Eucalyptus (genus Eucalyptus), a massive genus comprising around 660 species of shrubs and tall trees in the Myrtaceae family, is indigenous to Australia, Tasmania, and neighbouring islands [50].

Eucalyptus grow swiftly, and some species can reach great heights. In Victoria and Tasmania, the huge gum tree, or mountain ash (Eucalyptus regnans), grows to a height of roughly 90 metres (300 feet) with a girth of 7.5 metres (24.5 feet). Many species shed their dead outermost layer of bark in flakes or ribbons regularly, but others have thick, textured bark. The leathery leaves hang obliquely or vertically, and the majority of species are evergreen [50].

Photography 1. The leaves of the eucalyptus plant [50]

Fotografija 1. Listovi biljke eukaliptusa [50]

When the bloom grows, the petals stick together to form a cap. The capsule fruit, which contains numerous minute seeds, is surrounded by a woody cup-shaped receptacle [50].

3. AN OVERVIEW OF PREVIOUS WORK ON THE INHIBITION OF CARBON STEEL IN VARIOUS CORROSIVE ENVIRONMENTS BY THE LEAF EXTRACTS OF THE EUCALYPTUS PLANT

Many studies have employed eucalyptus plant extracts to lower the rate of corrosion of metals in acidic conditions. Table 1 summarizes the greatest inhibition efficiency achieved, as well as the corresponding inhibitor concentration.

Eucalyptus leaf extract has been used to prevent mild steel corrosion in hydrochloric acid solutions [51]. Following the addition of 800 ppm eucalyptus leaf extract, the corrosion rate fell from 0.93 μA/cm^2 to 0.25 μA/cm^2 after 5 hours. The maximal inhibitory efficiency was roughly 88%. The leaf extract's adsorption behaviour was shown to be consistent with the Langmuir isotherm model, while the polarization analysis demonstrated that the eucalyptus leaf extract influenced a mixed-type inhibitive behaviour. In a separate research, Abdulkhaleq [53] used eucalyptus camaldulens leaves to prevent corrosion of low-carbon steel in HCl (3M) media at various study temperatures ranging from 25 to 55 ^{0}C. After 46 hours of adding 8 g/L of the leaf extract, the maximal inhibitory effect of 91% was obtained. Furthermore, the efficiency of the inhibitory mechanism was found to rise as the concentration of the plant extract increased. The explanation for this development was linked to the adsorption of the extract's inhibitive elements on the surface of the mild steel to prevent additional corrosive environment attacks on the steel. In essence, the plant leaf extract's adsorption behaviour was determined to correspond with the Langmuir adsorption isotherm model.

Table 1. Summary of corrosion inhibition of mild steel in the corrosive environment by Eucalyptus plant extracts

Tabela 1. Rezime inhibicije korozije mekog čelika u korozivnoj sredini ekstraktima biljaka eukaliptusa

Inhibited material	**Study Environment**	**Study Method (s)**	**Part of the plant used**	**Maximum Inhibition Efficiency Attained (%)**	**Extract Concentration**	**Adsorption**	**Ref.**
MS	HCl (1 M)	EIS, PDP	Leaf	88	800 ppm	Langmuir	[52]
LCS	HCl (3 M)	WL	Leaf	91	8g/L	Langmuir	[53]
MS	HCl (5 %)	WL, EIS, PDP	Bark	98.2	900 ppm	Langmuir	[54]
CS	H_2SO_4 (1 M)	WL, PDP, EIS	Leaf	84	1.5 g/L	Langmuir	[55]
MS	H_2SO_4 (0.5 M)	PDP, EIS	Leaf	91	0.4 mol/L	Langmuir	[56]
	H_2P_4 (0.5 M)	EIS, PDP		78	0.2 mol/L		
LCS	H_2SO_4 (0.5 M)	Tafel, WL, EIS	Leaf	93.09	600 mg/L	Langmuir	[57]
CS	HCl (2 M)	WL	Leaf	91.56	0.08g/mL	Langmuir	[58]
	HCl (4 M)			85.68			
MS	NaCl	EIS, PDP	Leaf + Zn^+	90	600 ppm Zn^+ + 200 ppm of the extract 5.0g/L	Langmuir	[59]
MS	HCl (0.1 M)	WL	Bark	97.86		Langmuir	[60]
MS	HCl (0.5 M)	EIS, Tafel	Oil (essential)	91.1	-	Langmuir	[61]
LCS	H_2SO_4 (1 M)	WL	Leaf	84	120 ml	-	[62]
	H_2SO_4 (0.5 M)			86			
	H_2SO_4 (1.5 M)			75			

The bark extract of the eucalyptus plant has been researched for its ability to preserve mild steel against corrosion in HCl (5%) solution [54]. At 900 ppm concentration of the extract in an acidic medium, an inhibitory effect of 98.2% was found. Furthermore, the inhibitive disposition of eucalyptus bark extract was discovered to be mixed-type and consistent with the Langmuir isotherm model.

The use of eucalyptus globulus leaf extract to minimize carbon steel corrosion in H_2SO_4 (1 M) media has been explored [55]. The addition of 1.5 g/L of methanolic leaf extract of the eucalyptus plant in the aforementioned corrosive solution resulted in a maximum inhibitory efficacy of 84%. The inhibitive properties were discovered to be of the mixed kind and consistent with the Langmuir adsorption isotherm model. The adhesion of the extract on the surface of the carbon steel was thought to be the preventative mechanism that the leaf extract utilized to prevent corrosion, hence minimizing the aggressive response between the corrosive solution and the steel. In a similar work, Haldhar et al. [57] evaluated the use of eucalyptus globulus leaf extract to prevent corrosion of low-carbon steel in H_2SO_4 (0.5 M). After adding 600 mg/L of the plant's leaf extract, the inhibition effectiveness reached 93.09%. The adsorption characteristic of the plant extract was discovered to be consistent with the Langmuir adsorption isotherm model.

Abdel-Gaber et al. [56] investigated the use of eucalyptus leaf extract to suppress mild steel corrosion in both phosphoric (H_2PO_4) and sulphuric acid solutions. The addition of the extract to both acidic solutions lowered the rate of mild steel deterioration as the extract concentration increased. After adding 0.4 and 0.2 mol/L of eucalyptus leaf extracts to the corrosive media, the impedance (electrochemical) findings indicated 91 % and 78 %, respectively. The more persistent contact between the mild steel surface and the eucalyptus extract was credited with the leaf extract being more successful in preventing the corrosion of mild steel immersed in H_2SO_4 (1 M) than in H_2PO_4 (1 M). Physical adsorption was identified as the mechanism for the inhibitory process. Furthermore, the adsorption behaviour of the extract was discovered to correspond with Temkin and kinetic thermodynamic isotherm models.

A study has been conducted to reduce the deterioration of carbon steel in the H_2SO_4 (2 M and 4 M) medium [58]. At 20 ^{0}C, the maximal inhibition efficiencies after the addition of 0.08 g/L of the extract were 91.56 % and 85.68 % for the H_2SO_4 (2 M) and H_2SO_4 (4 M) solutions, respectively. The effectiveness of the leaf extract was observed to increase with increasing extract concentration but decrease with increasing temperature. In addition, the extract's adsorption disposition agreed with the Langmuir isotherm model. In another work, the inhibitive impact of the synergy of zinc ions (divalent) and eucalyptus plant leaf extract on mild steel corrosion in NaCl solution was investigated [59]. After 48 hours, the inhibitive materials combined in the following proportions: zinc ions (600 ppm) and eucalyptus leaf extract (200 ppm) achieved the greatest inhibition efficacy of 90 %. Additionally, the analytical analysis demonstrated that the adsorption mechanism that exists between the inhibitors is dependent on the acceptor-donor system.

Gupta et al. [60] used the bark of the eucalyptus plant to prevent mild steel corrosion in HCl (0.1 M). The presence of the inhibitor lowered the corrosion rate of mild steel in the acidic medium, but the inhibition efficacy decreased as the temperature increased. The greatest inhibitory efficiency reported was 97.86 %. In another work, Gualdron et al. [61] employed eucalyptus oil to prevent mild steel corrosion in HCl (0.5 M). Eucalyptus oil was determined to be a mixed-type inhibitor with a maximum inhibition effectiveness of 91.1%. In addition, Abdal-nabi et al. [62] studied the protection against corrosion of low-carbon steel using eucalyptus leaf extract at different sulphuric acid concentrations (1 M, 0.5 M, and 1.5 M). The inhibition efficiency dropped as the temperature increased from 25 to 60 ^{0}C, with the inhibition efficiencies dropping to 86 – 67 %, 84 – 59 %, and 75 – 52 % for 0.5 M H_2SO_4, 1 M H_2SO_4, and 1.5 M H_2SO_4 solutions, respectively.

4. IDENTIFIED GAPS IN KNOWLEDGE AND RECOMMENDATIONS

The review of previous studies on the use of the extracts of the eucalyptus plant to prevent the corrosion of mild steel in various acid concentrations has revealed the following gaps in knowledge:

1. It is true that different parts of the eucalyptus plant have been reported to give high values of inhibition efficiencies, but the combination of the parts to inhibit the corrosion of steel is yet to be adequately explored. Further studies to understand the influence of the synergy of the plant's parts to avert corrosion are recommended.
2. There is limited knowledge in the exploration of the active constituents of the eucalyptus extracts that were responsible for the inhibition process. Further studies are encouraged to identify in specific terms the active materials in the eucalyptus extract that inhibit corrosion.
3. There is a lack of predictive models that can forecast the corrosion rate of mild steel in the absence and presence of the eucalyptus plant. Further studies should be intensified in this direction.

5. CONCLUSION

After reviewing previous studies on the use of eucalyptus extracts to hinder the corrosion of carbon steels in several corrosive media, the following conclusions can be drawn:

1. The adsorption behaviour of the leaf and bark extracts of the eucalyptus plant were found to be of mixed type and predominantly obey the Langmuir adsorption isotherm model.
2. The inhibition efficiencies of the examined eucalyptus extracts were found to increase with concentration while their effectiveness was principally reported to reduce with a temperature rise.
3. The mechanism for the protection of the carbon steel from corrosion in different corrosive media by the eucalyptus extract was largely linked to the adherence of the inhibitive constituents of the extract on the surface of the steel to reduce the interaction between the metal and the corrosive surrounding.

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IZVOD

INHIBICIJA KOROZIJE UGLJENIČNOG ČELIKA LIŠĆEM EUKALIPTUSA U KISELOJ SREDINI: PREGLED

Ovaj rad se bavi pregledom prethodnih studija o koroziji i inhibiciji ugljeničnog čelika kome je dozvoljeno da se razgradi u korozivnom medijumu ekstraktom biljke eukaliptusa, sa naglaskom na adsorpcionom ponašanju ekstrakta. Mnogi istraživači su uglavnom koristili koru, ulje i ekstrakte listova eukaliptusa kako bi sprečili koroziju mekog čelika u kiselim sredinama pod različitim temperaturnim uslovima. Prema rezultatima, kada je ekstrakt kore biljke eukaliptusa dodat u HCl (5%) u koncentraciji od 900 ppm, maksimalna efikasnost inhibitora iznosila je 98,2 %. Ekstrakt lista je, s druge strane, imao maksimalnu inhibitornu efikasnost od 93,09 % pri koncentraciji ekstrakta od 600 mg/L u medijumu H_2SO_4 *(0,5 M). Pokazalo se da potencija ekstrakata opada sa povećanjem temperature. Mehanizam za zaštitu ugljeničnog čelika ekstrakta eukaliptusa od korozije u različitim korozivnim situacijama bio je u velikoj meri povezan sa adsorpcijom inhibitivnih komponenti ekstrakta na površini čelika kako bi se smanjila interakcija između metala i korozivne okoline. Većina prijavljenih inhibitivnih ponašanja ekstrakta eukaliptusa bila je u skladu sa modelom izoterme Langmuir adsorpcije.*

Ključne reči: *ekstrakt lista eukaliptusa, efikasnost inhibicije, meki čelik, model Langmuirove izoterme, inhibicija korozije, ugljenični čelik*

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