CHARACTERISATION AND INHIBITIVE EFFECT OF WATER EXTRACT OF *FICUS SUR* LEAVES ON THE CORROSION OF MILD STEEL IN HYDROCLORIC ACID SOLUTION

BY

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CERTIFICATION

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DEDICATION

This project research is dedicated to the Almighty God who in His infinite mercy saw me through my journey in the University of Benin, and to my loving parent.

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ABSTRACT

Corrosion is the deterioration of metal caused by chemical reactions or interactions with its surroundings. In order to address the issue of corrosion which is a major challenge in the metallurgical industry, there is need to introduce an inhibitor to combat this issue of corrosion. Before now, chemical inhibitors has been in use and because of the risk, toxicity and disadvantages of these chemical inhibitors, there is a current trend that is moving away from the use of chemical inhibitors to the use of green organic inhibitor that is sustainable and environmentally friendly. In this research work, the inhibition of corrosion on mild steel in 1M HCl solution was evaluated by utilizing *Ficus sur* extract which serves as the corrosion inhibitor. The synthesis of the *ficus sur* was done using the hot maceration method and the study of the corrosion rate was done using the gravimetric weight loss method and the concentrations of *Ficus sur* extracts used ranges from 0.0g (blank), 0.1g, 0.2g, 0.3g and 0.4g and the temperature was varied at three temperatures of 25°C (298K), 48°C (321K) and 60°C (333K).

From the result obtained it was shown that as inhibitor concentration increases, corrosion rate decreases following the gravimetric weight loss method used. Also adsorption studies were carried out using the Langmuir, Temkin and Freundlich models. From the adsorption studies carried out although they followed the three adsorption model, these research work best fit the Langmuir adsorption model which gives us $R^2 = 0.9931$.

The mild steel surface was also characterized using Scanning Electron Microscope (SEM) which provides a clear morphology of the metal surface.

CHAPTER ONE

INTRODUCTION AND LITERATURE REVIEW

1.1 INTRODUCTION

Nowadays, mild steel—also referred to as plain-carbon steel—is the most widely used type of steel due to its affordable price and suitable material qualities for a wide range of applications (D. K. Singh, et al. 2016). But the problem is that it has a low resistant to corrosion, particularly in acidic conditions. Acidic solutions are often employed in industrial processes such acid cleaning, pickling, descaling, and drilling operations in oil and gas exploration. As a result, iron and steel surfaces or vessels utilized in these conditions are susceptible to corrosion (M. V. Fiori-Bimbi, et.al 2015).

Due to its role in the degradation of materials, particularly metals and alloys utilized in nearly every industry, corrosion is a global concern. This is due to the fact that they are frequently subjected to acids during industrial procedures like acidizing oil wells, pickling and descaling in acid (M. Finšgar et al., 2014). Other significant corrodents 9 (sources of corrosion) in industries include water cut, oxygen, naphthenic acids, carbon dioxide, hydrogen sulfide, caustic alkalis and ammonium hydroxides, corrosion of steel at hydrocarbon electrolyte interfaces and in emulsified two-phase environments (K. Tamalmani, et al 2020).

1.1.1 BACKGROUND OF STUDY

Corrosion was a constant in the environment long before there were businesses, and stopping it or finding a cure has never been easy. 2. To remove mild rust and scale from steel and iron, strong acids like hydrochloric acid are frequently utilized in sectors connected to industries (Ibot et al., 2010). These inhibitors were employed by the industries due to their anti-corrosive properties, however they have certain detrimental effects on the environment.

Consequently, a group of seventeen eco-friendly corrosion inhibitors were created and dubbed Organic Corrosion Inhibitors (OCI) (Bommersbach et al., 2005). Corrosion can be stopped with either an inorganic or organic technique.

Another name for this strategy is Green Corrosion Inhibition. The corrosion inhibitor is one of the most well-known corrosion safety methods (Al-Otaibi, et al 2012).The first indication of the use of natural product extracts as corrosion inhibitors dates back to 1930.

For the first time, Chelidonium majus (Celadine) and other plan uh ts were used in an H2SO4 and sulphric acid media (Raja, et al. 2008).

Since they are plant extracts that are easily extracted, there is little to no pollution produced, and the process is economical. Generally speaking, organic compounds with heteroatoms that have aromatic rings, conjugated systems, conjugated aliphatic bonds, lone pairs of electrons (N, O, S, and P), and pi-electrons to be excellent corrosion inhibitors (Raja et al., 2008).

According to research, hexavalent chromium can cause irreversible harm to the nose, skin, eyes, and throat in addition to raising the risk of lung cancer (Herman, et al 2000). Since a similar universal anticorrosion chemical has not yet been discovered for use in coatings and primers, chromate replacements was problematic.

There are numerous industries where corrosion prevention is used. Medications have occasionally been investigated as corrosion inhibitors (Obot, et al 2009). Through combining fields like polymers, green chemistry has demonstrated throughout the years how fundamental scientific methods can profit from the preservation of both human health and the environment (Tao, et al. 2011). Being aware of corrosion and adjusting quickly, appropriately, and accurately.

1.1.2 STATEMENT OF PROBLEM

Hydrochloric acid and chromate compounds were widely utilized as inhibitors in the past. Note It has been noted that they are poisonous and further erode the metal's surface. Generally speaking, they are not sustainable and not really economical. This resulted in the development of affordable, eco-friendly inhibitors utilizing green sources.

1.1.3. RELEVANCE AND JUSTIFICATION OF RESEARCH

Firstly this research work is carried out to support the works of many other researchers who are solving the problem of environmental pollution by toxic compounds by using naturally occurring plant source such as; Ficus sur on corrosion inhibitors.

Secondly, to identify a more biodegradable, ecologically acceptable and renewable source of producing anti-corrosion materials.

1.1.4. SCOPE OF WORK

- To investigate the inhibitive properties of *Ficus sur* extract on mild steel
- To investigate the effect of temperature on mild steel

1.1.5 AIM AND OBJECTIVES OF THE STUDY

AIM

The aim of this research is to investigate the effect of corrosion rate in different concentration and temperature of *Ficus sur* which acts as corrosion inhibitor in mild steel in HCl solution.

OBJECTIVE

- The objective of this study includes the following:
- To prepare inhibitor from plant origin

- To determine the various phytochemicals present in the inhibitor.
- To examine inhibition efficiency of the prepared inhibitor in acidic medium, and
- To examine the effect of temperature on the mild steel in the acidic medium..

1.2 LITERATURE REVIEW

Metals are harmed by the corrosion process as a result of chemical or electrochemical reactions with their surroundings (P. Maaß, 2011). 3. When categorizing corrosion reactions based on the types of corrosive surroundings, they according to G.V. Redkina et al. (2020), are separated into wet and dry corrosion. Yu.I. Kuznetsov et al. (2020) have divided corrosion into various categories based on the morphology of metal damage. These include general corrosion, pitting corrosion, crevice corrosion, inter-granular corrosion, environmentally induced fracture, dealloying, galvanic, and erosion-corrosion.

Several techniques exist to prevent metal from corroding, including coating, alloying, cathodic and anodic protection, and more recently, surface application of a laser.

According to M. Hanoon et al. (2020), treating metal is thought to enhance its qualities, such as its hardness, resistance to corrosion, and roughness. Because they are widely used to reduce metallic waste during production and to lower the risk of material failure—both of which can result in the wabrupt closure of industrial processes and additional costs—corrosion inhibitors are extremely important practically. According to Al-Amiery et al. (2013), the utilization of corrosion inhibitors is crucial in halting the dissolution of minerals and minimizing acid consumption.

There are two types of corrosion reactions according to the nature of the corrosive environments: wet and dry corrosion (H. Herbert, et.al 2008). These types of corrosion can be classified into general corrosion; pitting corrosion; crevice corrosion; Inter-granular corrosion; environmentally induced fracture; de-alloying; galvanic, and erosion-corrosion; This is dependent upon how the metal damage is shaped (M. Hashim et al., 2019). Numerous methods, including coating, alloying, cathodic, anodic, and laser treatment, are employed to shield metals against rust. The main areas in which laser technology is used to treat materials' surfaces are those where the laser beam's unique properties set it apart from other energy sources and give it an advantage over all other traditional technologies—including contemporary ones—in this kind of heat treatment. J.R. Davies (2001). The growing use of lasers in material processing can be attributed to a number of special benefits that come with them, including high productivity, automation worthiness, non-contact processing that eliminates finishing operations, reduced processing costs, enhanced product quality, maximum material utilization, and minimal risk. (E.V. Kharanzhevskiy et al., 2020).

1.2.1 CORROSION DEFINITION

Corrosion is defined as the deterioration of a substance or its properties due to interactions between the substance and its environment (I. Adejoro et.al). Corrosion is degradation of materials characteristics as a result of interactions with their surroundings, and corrosion of the majority of metals—and many other materials, too—is an unavoidable consequence. Although most commonly related to metallic materials, degradation can occur to any kind of material. (B. Shaw and R. Kelly.2006).

1.2.2. MECHANISM OF REACTION

Metal corrosion is a localized (limited to a specific region) electrochemical reduction-oxidation reaction that happens on its surface and releases electrons as a result of in order to decrease hydrogen ions, to metal breakdown, and moved to a new spot on the surface (Brondel D. et al 1994). According to Wu W., Cheng G. et al. (2013), this process causes the metal to gradually deteriorate and eventually fail. Understanding the fundamentals of corrosion in carbon steel/HCl solution systems is essential before discussing different corrosion inhibition evaluation techniques.

Similar to numerous other metals, iron corrosion can be divided into two primary electrochemical reactions (Marcus P. et al.), the first of which is the anodic reaction (oxidative iron's disintegration). Equation (1) summarizes the total chemical reaction of iron immersed in HCl solutions, whereas Equations (2) and (3) show the anodic reactions of iron immersed in aqueous solutions and aqueous solutions containing Cl− ions. (D.K. Yadav and others).

(I) HCl solutions (overall chemical reaction):

$$Fe_{(solid)}+2H^{+}\rightarrow Fe^{2+}+H_{2(gas)}$$

(ii) Aqueous solutions (oxidative dissolution):

$$Fe+H_2O\Leftrightarrow[FeOH]+H^{+}+e^{-}$$

$$[FeOH]+H^{+}\Leftrightarrow Fe^{2+}+H_2O$$

(iii) Aqueous solutions containing Cl^{-} ions (oxidative dissolution):

$$Fe+H_2O+Cl-\Leftrightarrow[FeClOH]+H^{+}+e^{-}$$

$$FeClOH]+H^{+}\Leftrightarrow Fe^{2+}+Cl-+H_2O$$

The above equation makes clear that when iron is exposed to the aforementioned solutions, it tends to dissolve and release positive Fe ions into the electrolyte, which also creates free electrons that can pass through the metal.

1.2.3. FACTORS THAT CAUSES CORROSION

Natural processes such as the breakdown of metal components into their ores—oxides, sulfides, etc.—cause corrosion. This step releases the energy that was previously acquired during extraction and purification. Two As an electrochemical process, corrosion response that can take many different forms, including atmospheric and chemical corrosion. The existence of corrosive chemicals in the atmosphere is the reason why atmospheric corrosion is so frequent and pervasive. Rust is the resultant impact of corrosion. Steel dissolves into rust as a result of simultaneous exposure to oxygen and moisture and iron particles. (such as vapor, immersion, and humidity).

Among the contributing elements are:

- The metal exposure to air that contains gases such as CO_2, SO_2, and SO_3.
- Metals exposed to moisture, particularly seawater, which speeds up the rate of rust.
- Impurities, such as salt (NaCl), are present.
- Temperature: A temperature increase of 15 degrees causes corrosion to increase.
- The type of the initial oxide layer that formed. Certain oxides, such as aluminum oxide (Al_2O_3), can provide an impervious protective layer that stops more corrosion, while other oxides, similar to rust, readily crumble and reveal the remaining metals.

Corrosion can readily occur more quickly when there is acid in the atmosphere.

1,2,4 CLASSES OF CORROSION

Three main categories can be used to classify corrosion:

- Chemical and Electrochemical
- Temperature swings between high and low
- Corrosion, both wet and dry

In the absence of an aqueous environment, dry corrosion typically occurs in the presence of vapors and gases, and mostly at high temperatures. When it becomes a part of an electro-chemical cell, wet corrosion is the degradation of a metal. Here you need an anode, a cathode and an electrolyte. Each type of corrosion has a particular arrangement of anodes and cathodes, and locations with specific patterns based on the type which exists. The most important examples are:

Fretting Corrosion; Corrosion that occurs at touch areas among substances below load subjected to slide and vibration is called Fretting. Oxidation can occur at such friction in engines and automotive parts.

Pitting Corrosion Cavitation's or pitting damage: can be put as a unique form of erosion corrosion usually due to formation and collapse of vapor bubbles in liquids near a metal surface. Surface damages similar to pitting may 8 occur and both corrosion and mechanical factors are involved in this corrosion. Some factors which can influence crevice corrosion include: environmental situations together with pH, temperature, oxygen concentration, halide concentrations. This is a localized phenomenon often affecting smaller areas. Uniform Corrosion; This is an abundant form of corrosion found in ferrous metals-iron containing metal 8 and alloys that are not covered by surface coating or inhibitors. A uniform layer of rust on the surface environments is produced when exposed to corrosive material. A common example of this form is atmospheric corrosion.

Microbial Corrosion; This is a form of bio-deterioration and is frequently referred to as bacterial corrosion, bio-corrosion, microbiologically influenced corrosion, or microbial induced corrosion (MIC). This is corrosion caused by microorganisms, usually chemoautotrophs: organisms that manufacture their food through chemical reactions (catabolism)

1.2.5 METHOD USED IN PREPARATION OF PLANT EXTRACT

An extract is a solution composed by the active principles of a plant or its parts and a certain medium acting as solvent.

The polarity of the solvent used in the procedures (Soxhlet and maceration), among other things, affects the extraction yields.

The extract's active principles provide the qualities for a specific function. Consequently,

Certain plants can have certain advantages depending on their concentrations and active ingredients. The main benefits of these extracts are their antibacterial, antiviral, anti-inflammatory, and antioxidant properties. Furthermore, their ability to suppress corrosion may be viewed as a synergistic impact. Typically, extracts are made from the entire plant or from the sections that have higher concentrations of active ingredients known as phytochemicals. (Marsoul and others, 2020).

Plant, fruit, seed, flower, and leaf extracts have been shown in the literature to contain active compounds that show promise for inhibiting corrosion in harsh media. Furthermore, these substances become affordable, widely accessible, and renewable substitutes for corrosion inhibitors [Dehghani] et al. 2020). It is therefore required to review the novel plant extracts that have been shown to be extremely effective corrosion inhibitors. The goal of this review is far outweighed by the wide range of extraction techniques that are currently in use. Below is a quick overview of extraction techniques, though.

The first step is to identify the plant section that contains the highest concentration of the target active compounds.

To make the extracts, all parts of the plant—leaves, flowers, seeds, fruits, roots, and stems—are utilized. The basic principles of extraction techniques involve heating, cooling, and isolating the active ingredients while the solvent is present. Second, according to Handa (2008), classic extraction techniques can be summed up as follows: maceration, infusion decoction, digesting, and olation. Generally speaking, the extract method's form is appropriate based on the desired outcome.

1.2.5.1 MACERATION

Separating solids from liquids using either water or an organic solvent as the liquid phase is the basis of maceration extraction. Most commonly, alcohol and water, or both together, are used in the maceration process, which is carried out at room temperature.

While fungal contamination can arise during lengthy maceration in water, it does not happen in alcohol solutions. Maceration is the process of immersing crushed, smashed, or sliced materials—sometimes dried beforehand—into the extraction solvent while stirring constantly for at least three days.The active chemicals are solubilized by the solvent's diffusion into the targeted substance, which opens the door to potential extraction.

Filtering is a useful technique for separating the suspended solids in the final mixture. The benefit of this approach is that the active components are readily soluble and the entire essence is extracted without modification. Through brief maceration in the presence of hot water, the infusion process produces the extract. As a result, the components that are highly soluble become soluble and go into the extract.

1.2.5.2 DECOCTION

Decoction process, the crude drug is boiled in a specific volume of water for a defined time. The digestion method proposes the maceration of the raw materials in the presence of a slightly warm solvent, improving the solubility of the extraction solvent and preserving the active compounds from decomposition.

1.2.5.3 PERCOLATION

Percolation is a room-temperature filtration technique where the raw material is moistened and put in a conical vessel called a olator that has an adjustable lid. To acquire the extract drop by drop, the olator needs to be filled with solvent and covered (Zhang et al 2018). Percolation has several benefits, including high performance active ingredients, quick manufacturing times, and economical resource usage.

1.2.5.4 MODERN EXTRACTION TECHNIQUES

Hot continuous extraction and ultrasound extraction, often known as sonication, are more advanced techniques (Azmir et al 2013). The first one makes use of the Soxhlet apparatus, which is composed of a condenser, siphon arm, thimble, extraction chamber, and glass body with boiling flask. To put it briefly,

The solvent-containing boiling flask is heated, and the resulting vapor is condensed.

The liquid that is left over pours into the thimble that held the raw material. The extract then fills the extraction chamber, activating the siphon arm and transferring the liquid back into the boiling flask. In order to achieve the required level of extraction, the reflux process needs to be stopped.

Lastly, sonication is a method that produces cavitation to damage cellular membranes by increasing the permeability of cell walls through the use of high frequency ultrasounds.

As a result, the cells are broken down by sonication, which releases their contents for additional extraction. Filtration or decantation are the next steps used to clarify liquids obtained using the previously described procedures.

Since the solvent is what solubilizes the active chemicals as they permeate through plant tissues, enabling their extraction, it plays a crucial part in the extraction processes. Since the concentration of flavonoids, saponins, phenolic compounds, and other chemicals present in plant extracts varies depending on the extraction solvent, it has been demonstrated that extraction solvents have an impact on the physical, chemical, and antioxidant properties of the extracts obtained (Seal, T. 2016).

As a result, different solvents have been employed to get plant extracts to contain the appropriate amount of active ingredients. Next, the type of solvent utilized determines how well active chemicals are extracted; the most popular types of solvents include water, dichloromethane, hexane, methanol, and ethyl acetate. Given its abundance, low cost, non-toxicity, and non-flammability, water may be the most practical extraction solvent (Duan, H. et al., 2015).

It is possible to test alternative solvents because not all plant extracts are available as aqueous extracts. Because of this, solvents are selective, and testing multiple alternatives is necessary to achieve the best yield.

Drying and temperature of the extraction are two more crucial extraction process factors.

The first one indicates the temperature at which the plant should dry; however, as plants are often dried in the shade, room temperature is typically employed. Using dried plants has advantages because they are lighter and can be stored for a longer period of time. On the other hand, drying has been demonstrated to have an impact on antioxidant capacity and the stability of bioactive substances. Although using fresh plants instead than dried ones may have certain disadvantages,

Solar radiation may cause fresh plants to deteriorate, and some of their components may oxidize or evaporate more quickly. On the other hand, phytochemicals may occasionally be extracted in greater

concentrations obtained using fresh samples as opposed to dried ones. An further crucial factor is the extraction temperature, as a low temperature decreases the solubility of active compounds and impedes their extraction, while a high temperature encourages the breakdown of phytochemicals. The right selection of extraction temperatures, extraction costs, solvent, and other factors is necessary to obtain the ideal concentration of phytochemicals (Mo. S et al 2016).

1.2.6 FICUS SUR

Ficus sur is a deciduous or evergreen tree that grows quickly. Its typical growth range is 5 to 12 meters (16 to 39 feet), however it can reach up to 35 to 40 meters (115 to 131 feet) in height (Hankey, Andrew 2003). Big examples grow a large, fluted crown that spreads outward.

roots that reinforce the stem. Ficus sur belongs to the Moraceae family. The figs are edible, and indigenous people in many areas use them either fresh or dried. If additional suitable fruit is added, they can also be used to prepare fig preserves.

FIGUR 1 *Ficus sur* fruit and tree

Figure 2. Dried *Ficus sur* leaf

1.2.7 CORROSION INHIBITOR

The corrosion inhibitor stands out as an effective and cost-efficient method widely used in the industry to prevent metal surface damage or degradation (Maaya et al., 2004). It is recognized as a primary corrosion protection measure, functioning by significantly reducing the corrosion rate of materials, particularly metals, in various environments, including acidic conditions (Camila et al., 2014). This approach is favored for its affordability and straightforward application. Substantial research has been conducted, especially in areas like the development of new shale gas pipelines and construction growth, with a focus on government spending (Maaya et al., 2004).

1.2.8 PROPERTIES OF A GOOD INHIBITOR

An effective inhibitor distinguishes itself through qualities related to its performance, influenced by physical and chemical properties, as well as its interaction with the metal surface. Soft molecules, characterized by a small energy gap, are more effective inhibitors compared to hard molecules with a large energy gap, as the latter do not perform well due to their limited interaction with electrons. Additionally, higher electronegativity in a molecule enhances bond formation or adsorption, impacting its ability to form complexes with the metal by accepting electrons. It is crucial for the inhibitor to be less electronegative than the metal to facilitate electron attraction from the ligand.

1.2.9 CLASSIFICATION OF GREEN CORROSION INHIBITORS

Green corrosion inhibitors can be divided into two categories: organic green inhibitors, which consist of synthetic substances that are environmentally non-toxic (K.Tamalmani et.al 2020), and inorganic green inhibitors, widely used in aqueous systems due to their high efficiency (M.Bethencourt et.al 1998). According to H.Wei et al. (2020), organic green inhibitors offer advantages over their inorganic counterparts. Figure 1 illustrates the classification of green corrosion inhibitors into different groups.

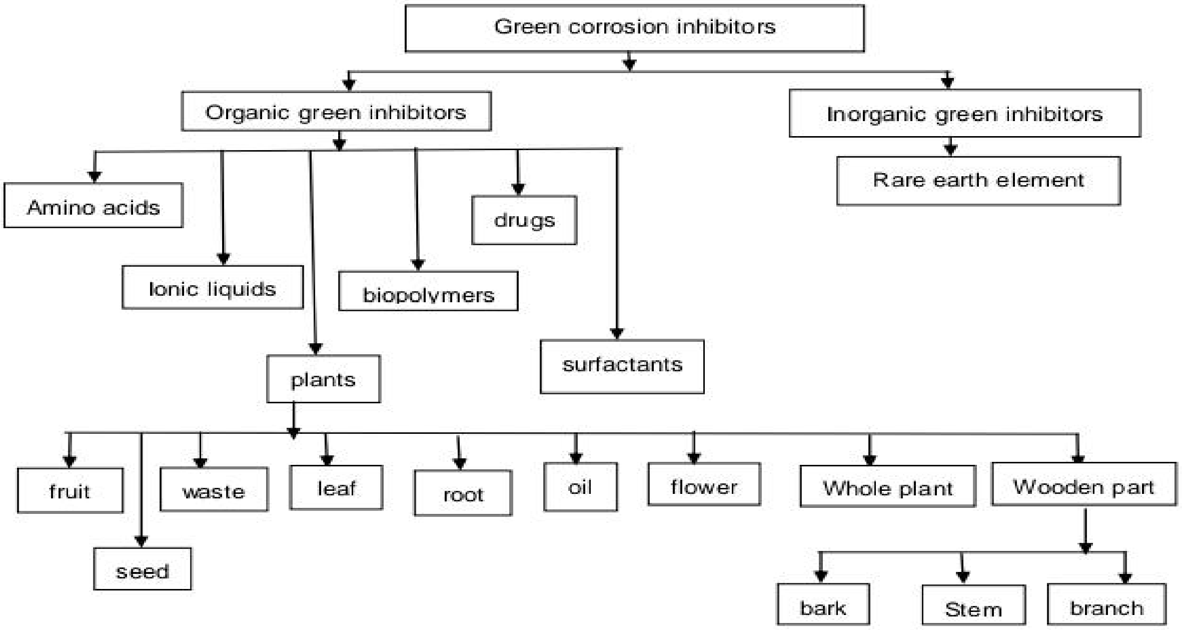

FIG.3 Classification Of Green Corrosion Inhibitors

1.2.10 INORGANIC CORROSION INHIBITORS

Inorganic inhibitors are substances where the active component is an inorganic compound. Introducing electropositive metal salts to a corrosive environment represents a straightforward method to enhance the passivity of a metal. It is crucial for the protective metal ion to possess a redox potential higher than the metal requiring protection and exceeding the potential necessary for proton discharge. This ensures the deposition of the protective metal ion onto the surface of the metal in need of safeguarding, resulting in cathodic depolarization and the subsequent formation of a secure deposit. Palladium (Pd), platinum (Pt), iridium (Ir), rhodium (Rh), mercury (Hg), and rhenium (Re) are examples of metals fulfilling this role. Moreover, various inorganic anions like chromates (CrO4 2−), molybdate (MoO3 −), silicates (SiO4 4−), phosphate (H2PO3 −), and nitrate (NO2 −) also contribute to providing passivation protection by integrating into the oxide layer on metal surfaces (Palou RM et.al. 2011).

1.2.11 ORGANIC GREEN CORROSION INHIBITORS

The exploration of Organic Corrosion Inhibitors is an intriguing field due to their versatility across industries. The effectiveness of these inhibitors relies on the stability of the chelate formed, necessitating inhibitor molecules with centers capable of bonding to the metal surface through electron transport. Typically, organic inhibitors displace water molecules on the metal surface, creating a protective barrier. The presence of non-bonding electrons and p electrons in these inhibitors facilitates electron transfer to the metal. The efficiency is closely tied to the chelate's stability, determined by the type and nature of alternatives in the inhibitor molecule (A. Kadhim et.al 2017).

In 2011, (I.O. Ogunleye et al) investigated grapefruit juice's impact on mild steel corrosion rates in various acidic media (HCl and H2SO4). Grapefruit juice concentrations from 0% to 5% were employed, revealing a reduction in corrosion rates, with inhibitor efficiency reaching 94.6% and 75.8% at a 5% concentration for HCl and H2SO4, respectively. This suggests that grapefruit juice acts as a superior corrosion inhibitor in HCl compared to H2SO4.

In 2013, N.S. Patel et al. utilized corrosion inhibitors derived from plant leaves to diminish mild steel corrosion rates in 0.5 M H2SO4. Using techniques like the weight-loss method and electrochemical polarization, they demonstrated that plant leaf extracts serve as excellent corrosion inhibitors. Scanning electron microscopy revealed a protective layer on the mild steel surface, rendering it more resistant to corrosion due to the adsorption of active molecules.

A. Kadhim examined the anti-corrosion activity of the Schiff base 3-[(5-phenyl-1,3,4-thiadiazol-2-yl)imino]-2-oxoindoline on mild steel corrosion in 1 M hydrochloric acid. Weight loss measurements and scanning electron microscopy indicated increased inhibition efficiency with rising compound concentration. The inhibitor operated through adsorption following the Langmuir isotherm, with electronic properties derived from the Austin Model 1.

- Corrosion inhibitors function through:
- 1. Creating a film that adheres to the metal surface.
- 2. Generating corrosion products, such as iron sulfide (FeS), which serves as a passivator.
- 3. Producing precipitates capable of removing or deactivating aggressive components (Umoren SA et.al 2010).

Depending on the electrochemical reactions they impede, film-forming or interface inhibitors can be categorized as anodic, cathodic, or mixed-type. Anodic inhibitors, also referred to as passivation inhibitors, slow down anodic reactions by generating sparingly soluble deposits, such as hydroxides, oxides, or salts, particularly in near-neutral conditions. Conversely, cathodic inhibitors reduce the rate of cathodic or reduction reactions by forming a protective layer on cathodic regions, protecting against hydrogen in acidic conditions and oxygen in alkaline conditions. Mixed inhibitors impact both anodic and cathodic reaction sites by establishing an adsorptive film on the metal surface, with around 80% of organic inhibitors falling into this category. Based on their chemical composition, inhibitors can be categorized as organic or inorganic. Moreover, considering their compositions and mechanisms, organic and inorganic inhibitors can be further classified into neutralizing, scavenging, barrier or film-forming, and other miscellaneous inhibitors (Garverick L. 1994).

Organic inhibitors function by creating a protective film on metal surfaces, serving as either anodic, cathodic, or mixed inhibitors. The formation of this film relies on robust interactions like π-orbital adsorption, chemisorption, and electrostatic adsorption, preventing corrosive species from attacking the metal. Typically, this adsorption forms a single molecular layer without penetrating the metal's bulk. Physicochemical properties, including functional groups, steric factors, aromaticity, π-orbital character for electron donation, electron density at donor atoms, and molecular electronic structure, govern the adsorption process. The corrosion inhibition effectiveness of an organic inhibitor depends on its adsorption capability and the mechanical, structural, and chemical characteristics of the adsorption layers in a specific environment. A proficient organic inhibitor usually features polar functional groups containing S, O, or N atoms and a hydrophobic component that repels aqueous corrosive species from the metal surface. However, the polar head plays a crucial role in establishing the adsorption layer. Various chemical families of organic inhibitors include pyridines, fatty amides, imidazolines, and 1,3-azoles (Palou RM. Et.al 2011).

Factors like environmental friendliness, cost, availability, and toxicity should significantly influence the choice of an inhibitor for specific conditions. The concern over the toxicity, biodegradability, and bioaccumulation of conventional corrosion inhibitors released into the environment is substantial. While the full environmental implications of commercial corrosion inhibitors remain unclear, it is well-known that their chemical components can have hazardous effects. Inorganic inhibitors, including arsenates, phosphates, chromates, and dichromates, exhibit promising inhibition efficiency but are proven to be intolerant due to their potential long-term threat to social health. Similarly, the ecological and health risks associated with organic inhibitors have prompted the exploration and utilization of non-toxic or green corrosion inhibitors. These alternatives aim to provide maximum protection to metallic structures with minimal impact on both humanity and the environment (Sabirneeza. AAF. et.al. 2015).

Corrosion inhibitors play a crucial role in safeguarding metals and equipment, necessitating them to be environmentally friendly, non-toxic, and acceptable. The awareness raised by the cost and adverse effects linked with conventional organic and inorganic inhibitors has led corrosion scientists and engineers to prioritize the use of green corrosion inhibitors. These alternatives are cost-effective, easily accessible, environmentally friendly, ecologically acceptable, and renewable.

In a study conducted by Ambrish Singh et al. in 2012, the impact of Punarnava (Boerhavia diffusa) extract on mild steel corrosion was investigated using gravimetric, potentiodynamic polarization, and electrochemical impedance spectroscopy. The findings indicated that the extract functioned as a mixed-type inhibitor, with the maximum displacement of -Ecorr value being 46 mV, as observed from tafel polarization curves. The inhibition efficiency reached up to 96% at 300 ppm and decreased with rising temperature. The charge transfer resistance (Rct) of the inhibited system increased from 68 W cm2 to 426 W cm2, while the double-layer capacitance (Cdl) decreased from 37 μF cm-2 to 17 μF cm-2 with an increase in inhibitor concentration. The inhibitor molecules adhered to the steel surface following the Langmuir adsorption isotherm. The extract demonstrated high efficiency, supported by a low energy gap (ΔE). Weight loss measurements at 308 K were utilized to determine the corrosion rate and inhibition efficiency values for mild steel corrosion in 1 M HCl, both in the absence and presence of different concentrations of Punarnava (Boerhavia diffusa) extract, with efficiency ranging from 73% to 96% for concentrations up to 300 ppm.

In 2006, Emeka E. Oguzie conducted a study on the corrosion inhibition of mild steel in 2M HCl and 1M H2SO4 using leaf extracts of Occimum viridis (OV) through the gasometric technique at temperatures of 30°C and 60°C. The findings revealed a direct relationship between inhibition efficiency and concentration, indicating that the extracts effectively inhibited the corrosion process in both acidic media. The presence of halide additives, namely KCl, KBr, and KI, enhanced the inhibition efficiency through synergistic effects. Temperature investigations demonstrated a decrease in efficiency with increasing temperature, while corrosion activation energies increased in the presence of the extract, suggesting that physical adsorption of cationic species might be responsible for the observed inhibition behavior. A comparative analysis of the inhibitor adsorption behavior in 2M HCl and 1M H2SO4, along with the effect of halide additives, suggested that cationic species may not be the sole constituents responsible for the inhibiting action of the extract. Plots depicting the variation of inhibition efficiency with OV extract concentration indicated that the extract effectively inhibited the acid corrosion of mild steel, with inhibition efficiency increasing with higher extract concentrations at both 30°C and 60°C temperatures.

In 2020, Haldar et al. conducted an assessment using Eucalyptus globulus leaves extract on low carbon steel immersed in a 0.5 M H2SO4 solution to evaluate its corrosion inhibition properties. Weight loss and electrochemical impedance spectroscopy (EIS) were employed for this analysis. The results indicated that the Nyquist diagram achieved a maximum value in the real section of impedance, reaching approximately 250 W cm2. The extract exhibited the highest corrosion inhibition of 93% at a dosage of 600 mg/L. The establishment of coordination interactions between inhibitor molecules and Fe2+ was verified using UV-VIS spectroscopy. SEM and AFM tests were employed to confirm the creation of a corrosion-protective coating on the metal surface. Furthermore, FT-IR and proton-nuclear magnetic resonance (1H NMR) techniques were utilized to examine various functional groups, including heteroatoms and unsaturation, within the phytochemical elements of the plant extract.

In 2014, R.C. Chhipa utilized the weight loss method to assess the corrosion of mild steel in different concentrations of hydrochloric acid and sulfuric acid, both in the absence and presence of extracts from the seeds of the Pennisetum glaucum plant. The study concluded that corrosion inhibition increased proportionally with the concentration of the extract. It was found that the seed extract from the Pennisetum glaucum plant is effective and exhibits high corrosion inhibition efficacy. Additionally, the research revealed that mild steel is more susceptible to corrosion in acidic solutions such as HCl and H2SO4.

S. Akbarzadeh et al. (2020) investigated the effectiveness of a green corrosion inhibitor derived from Tamarindus Indica (TAM) extract and zinc nitrate (ZS). Mild steel was exposed to a 3.5% NaCl corrosive medium, and after a 24-hour immersion, electrochemical impedance spectroscopy (EIS) indicated synergistic activity, achieving 96% corrosion inhibition efficiency with 300 ppm TAM and 700 ppm ZS. Polarization spectrum data in the TAM and ZS mixture showed a predominant anodic depression behavior. Field emission SEM and grazing incidence XRD confirmed the formation of a uniform protective layer.

In a study conducted by M.B. Harb et al. in 2020, olive leaf extract was tested in a corrosive solution of 0.1 M NaOH + 0.5 M NaCl. The research revealed that the inhibitory efficiency increased with greater polarity, while methanol, ethyl acetoacetate, hexane, and dichloromethane led to a reduction in inhibitory efficacy. The highest inhibitory efficiency, reaching 91.9%, was observed with the methanol extract. Gas chromatography and mass spectrometry analysis suggested that the inhibitory action might be linked to the presence of nitrogen, oxygen, and π-electrons. The extract was identified as rich in phenols and flavonoids, leading the researchers to classify it as a mixed inhibitor based on potentiodynamic polarization (PP) studies. EIS and Mott Schottky analyses aligned with the findings from PP.

A study by Ahanoto et al. in 2020 demonstrated the effectiveness of Pterocarpus santalinoides (PS) leaf extract in inhibiting corrosion in low carbon steel exposed to a 1 mol/dm3 HCl solution. The protective ability of the extract increased with higher dosage and temperature, reaching nearly 90% shielding at 333.15 K. Their findings suggested that the extract serves as a mixed-type corrosion inhibitor, and AFM measurements revealed minimal surface penetration, contrasting with observed corrosion in the absence of the extract. Solvent extraction comparisons indicated that ethanolic and methanolic extracts outperformed aqueous extracts, possibly due to their enhanced flavonoid extraction efficiency, recognized as effective inhibitors for carbon steel.

MATERIALS AND METHOD

2.1. MATERIALS

- Dried *Ficus sur*
- Electric blender
- Funnel
- Filter paper
- Beaker
- Foil paper
- Boiler
- Stirrer
- Water bathe
- Rotary evaporator
- Weighing scale
- SEM machine
- FT-IR machine

REAGENTS

- Hydrogen chloride
- Distilled water
- Acetone

The solutions 1M HCl were prepared by dilution of an analytical reagent grade 35.5-37.5% HCl with distilled water.

2.2. PREPARATION OF MILD STEEL

The mild steel coupon utilized in this study was sourced from Yongxing Steel Co. Ltd in Benin City, Nigeria. The coupon, measuring 1.21 cm, underwent polishing with sandpaper and emery paper to eliminate dirt and rust, followed by cleaning with acetone. Afterward, the samples were dried, weighed, and their respective weights were recorded and labeled.

2.3 METHOD OF PREPARING AND EXTRACTION OF THE PLANT EXTRACT

The Ficus sur plant was sourced from Ovia North East local government area, Benin City, Edo State. Its leaves were air-dried for two weeks, then ground using a clean electric blender. The powdered sample was combined with hot distilled water through hot maceration in an 800ml beaker covered with foil and left overnight. Afterward, the mixture was filtered using Whatman's filter paper. The resulting extract was concentrated using a rotary evaporator and divided into separate beakers, each containing a specific concentration (0.1, 0.2, 0.3, and 0.4).

2.4 GRAVINETRIC METHOD

In the experiment, a weight loss method was applied as follows: Each coupon's weight (W0) was measured using an analytical weighing balance. The coupon was then placed in a 250mL beaker, and 100mL of 1 M HCl was added. The setup was kept in the laboratory away from direct sunlight, with exposure times for each coupon carefully recorded. At intervals of 3 hours, the coupons were removed, washed in methanol to halt corrosion, and dried with acetone. Post-corrosion, the coupons were reweighed, and the final weights (W1) were recorded. Weight losses ($\Delta W = W0 - W1$) were calculated. Inhibition efficiency (% IE) and surface coverage (θ) were determined using specific equations (2&1), where W1 and W0 represent weight loss values in the presence and absence of the inhibitor, respectively. The experiment was repeated with plant extract concentrations of 0.1, 0.2, 0.3, and 0.4g in the 1 M HCl medium, over varying time intervals of 3 hours.

$$\theta = \frac{W_0 - W_1}{W_0} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots . (1)$$

$$\%IE = \frac{W0-W1}{W0} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The corrosion rate (CR) is expressed as an increase in corrosion depth per unit time in ($mgcm^{-2}h^{-1}$). The corrosion rate equation is given as:

$$CR = \frac{\Delta W}{At} \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where Δw = weight loss of coupon, t = immersion time, and A=area of coupon

2.5. ADSORPTION STUDIES

2.5.1. Freundlich isotherm

The Freundlich isotherm is valuable in explaining equilibrium data and adsorption behaviors on a surface with heterogeneity. It applies to both monolayer (chemisorption) and multilayer adsorption (physisorption). The equation is typically represented in a linear form as follows:

$\log \Theta = \log K_{ads} + \frac{1}{n} \log C \ldots \ldots \ldots (4)$

Where K_{ads} Freundlich isotherm constants related adsorption capacity and n is the adsorption intensity respectively, Θ is the surface coverage. C is the inhibitor concentration

The constant K is an estimated indicator of adsorption capacity, while 1/n is a function of the strength of adsorption in the adsorption process.

2.5.2. Langmuir isotherm.

- The Langmuir theoretical equation was formulated under the assumptions that a constant number of accessible sites exist on the adsorbent surface, all possessing uniform energy levels. Additionally, the process of adsorption is considered reversible, and once a site is occupied by an adsorbate, no further adsorption can take place on that specific site.
- no interaction occurs between adsorbed species.

The linear form of the isotherm is described as

$$\frac{Ce}{\theta} = \frac{1}{Kads} + Ce \ldots\ldots\ldots\ldots (5)$$

Where Kads (mg/L) is the Langmuir constant related to affinity between and adsorbent and adsorbate, Θ= % IE/100 the maximum saturated monolayer adsorption capacity of an adsorbent.

2.5.3. Temkin Adsorption Isotherm.

The Temkin adsorption isotherm equation shown as

$e\text{-}^{2a\theta} = K_{ads} C \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$

$\theta = \frac{-2{\cdot}303 \, log \, kads}{2a} + \frac{-2{\cdot}303 \, log \, c}{2a} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$

Where, C is a concentration of inhibitor, θ is a fraction of surface coverage area, Kads is adsorption equilibrium constant.

2.6 PHYTOCHEMICAL INVESTIGATION

Phytochemical constituents such as alkaloids, flavonoids, saponins, steroids, tanins, phenolic compounds, proteins and reducing sugars of the leaves were determined using the methods described by Trease and Evans 1996 and Sofowara 2006.

2.7 SEM Analysis

Scanning Electron Microscope (SEM) provides a clear comparison between the metal surface with and without a corrosion inhibitor, as well as other morphological information.

2.8 FT-IR Analysis

Fourier transform infrared (FTIR) spectroscopy is employed to gather details about the functional groups and vibrational modes present in corrosion inhibitors. As a well-established quality management technique for assessing material synthesis, it represents the initial step in the material analysis process. Particularly effective for examining chemical components of smaller particles, typically around 10-15 microns, this method utilizes infrared energy to scan test samples and observe their chemical properties. The FT-IR instrument introduces infrared radiation ranging from about 10,000 to 100 cm-1 through the sample. Some of this radiation is absorbed, while the remainder is transmitted. The absorbed radiation is then converted into vibration and/or rotational energy by the molecules within the sample.

2.9 TEMPERATURE VARIATION

To carry out the isotherm studies, the already weighed metal strips were put in beakers containing different concentrations of the inhibitor ranging from 0.1 to 0.4g/100ml in 1M HCL and the control solution without inhibitor. The temperature was varied from 25^{o}C, 48 ^{o}C and 60 ^{o}C in the thermostatic water bath. The process was repeated for the various temperatures considered. After which the metal strips were retrieved, rinsed in distilled water, followed by ethanol so as to remove possible grease and dried with acetone and the weight was determined again.

CHAPTER 3

RESULT AND DISCUSSION

3.1. WEIGHT LOSS MEASUREMENT

The loss in weight of mild steel in corrosive environment of 1M HCl (with and without concentrations of *Ficus sur* extract for 3h, 6h, 9h and 12h) was determined at 25 ◦C and 48 ◦C, and 60 ◦C.

Concentration	25°C (ΔW)	48°C (ΔW)	60°C (ΔW)
Blank	0.8620	1.834	2.492
0.1	0.4940	0.832	1.380
0.2	0.4510	0.563	0.910
0.3	0.3810	0.319	0.730
0.4	0.3630	0.171	0.542

Table 1 Temperature Effect on Corrosion of Mild Steel in 1M HCl Solution Containing Various Concentration of Water Extract of *Ficus sur*

3.2 EFFECT OF VARIOUS TEMPERATURE ON CORROSION RATE

The weight loss experiment performed at temperatures of, 25°C, 48°C and 60°C in 1M HCl solution containing varying concentrations of the water extracts of *Ficus sur* revealed that the corrosion rate of mild steel increased with temperature but decreased with increase in extract concentration as a result of increase in surface weight loss. (See Tables 1). Corrosion rate is related to inhibition efficiency (Table 2). It was discovered that IE% rises with increasing extract concentration. This might be due to mild steel disintegration and partial desorption of the Phyto-inhibitor from the mild steel's surface.

Concentration	ΔW	CR	θ	I.E%
Blank	0.8620	0.024	-	-
0.1	0.4940	0.0138	0.4269	42.69
0.2	0.4510	0.0126	0.4770	47.68
0.3	0.3810	0.0106	0.5580	55.80
0.4	0.3630	0.0101	0.5800	58.00

Table 2. Results of Weight Loss, Corrosion Rate, Surface Coverage and Inhibition Efficiency of *Ficus sur* Extract on Mild Steel in 1M HCl solution

3.3 FT-IR STUDY

The result of the FT-IR spectrum of *Ficus sur* extract can be seen in Fig. 4; A strong broad peak at 3339.7 cm-1 corresponds to O-H bond stretching vibrations. It indicates that the sample contains hydroxyl (OH) functional groups such as alcohols, phenols, and other substances frequently include hydroxyl groups which contain antioxidant properties and can contribute to the plant's defense against stressors. A sharp peak at 1558 cm-1 is associated with N-H bend stretching vibrations. A sharp peak at 1408.5 cm-1 is associated with C-H bend stretching vibrations. This peak shows the presence of aliphatic hydrocarbons, which are present in alkanes and alkyl groups, they form hydrophobic barrier repelling water from the surface of the metal and help to limit the availability of oxygen at the metal surface. A peak at 1021.3 cm^{-1} corresponds to C-O stretching vibration of primary alcohol.

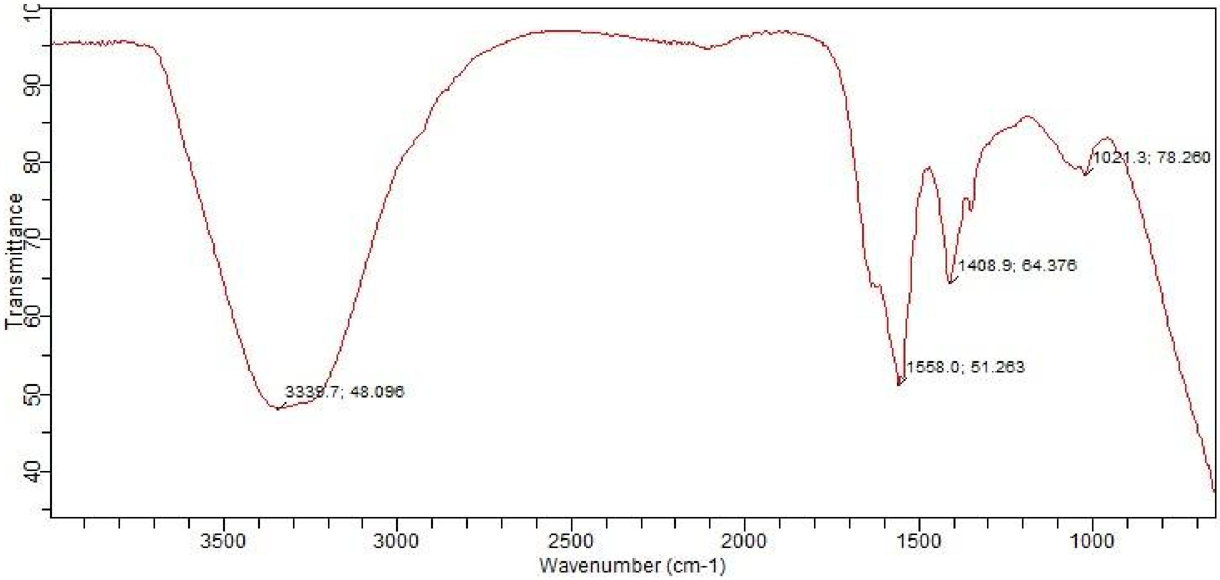

FIGURE 4. FT-IR of the *Ficus sur* extract.

3.4 ADSORPTION ISOTHERM

In adsorption studies, the formation of a coating or film on the surface of a solid or liquid medium is analyzed. The effectiveness of inhibition is intimately correlated with the adsorption of inhibitor molecules on the metal sheet. For the objective of evaluating the kind of adsorption of *Ficus sur* extract components on target adsorbent, a number of adsorption mechanisms were investigated. Physical adsorption (physisorption) and chemical adsorption (chemisorption) are two different types of adsorption. Weak van der Waals forces are involved in physisorption, whereas chemical bonds are formed between the adsorbent and adsorbate in chemosorption.

The Langmuir, Temkin, and Freundlich isotherms were used to match the experimental findings, and the results are displayed below.

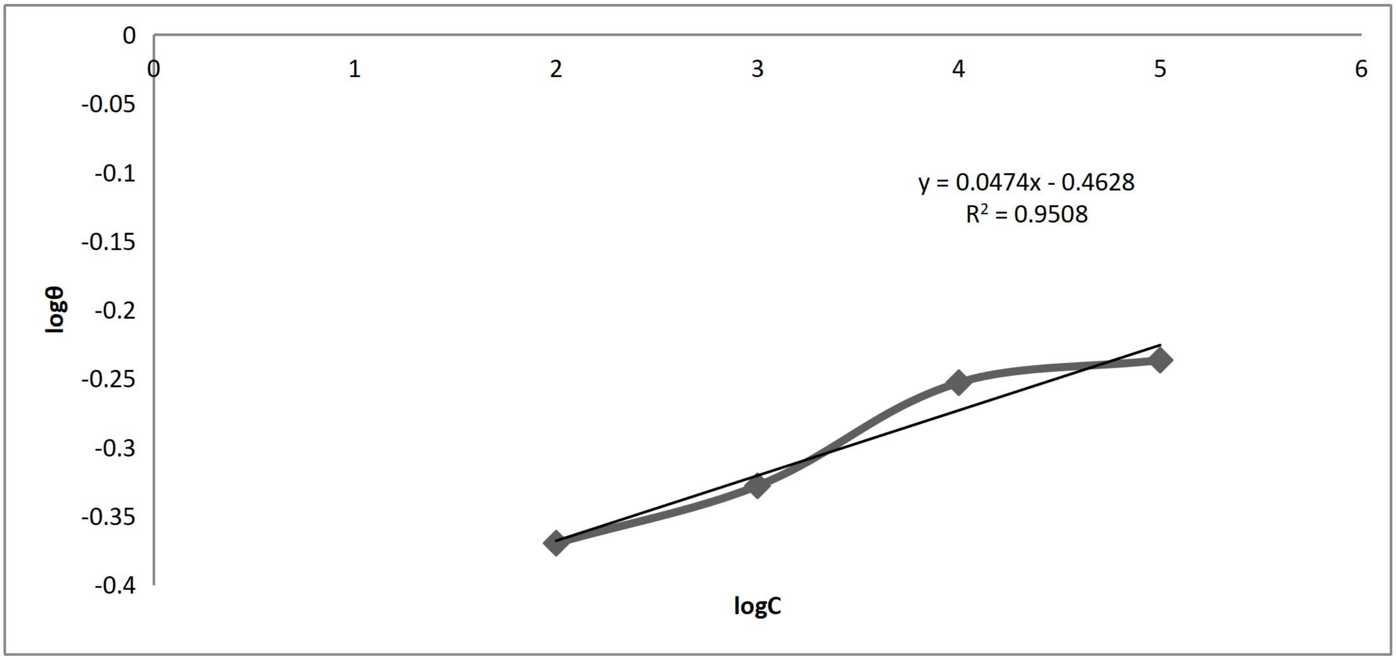

Figure 5; Freudlich Adsorption Isotherm Plot for Corrosion of Mild Steel in Extract of *Ficus sur* Extract In 1m HCl At 3hours.

From Fig. 5, the R^2 value obtained is 0.9508, showing the adsorption of *Ficus sur* extract on metal used for this study follows Freundlich adsorption isotherm.

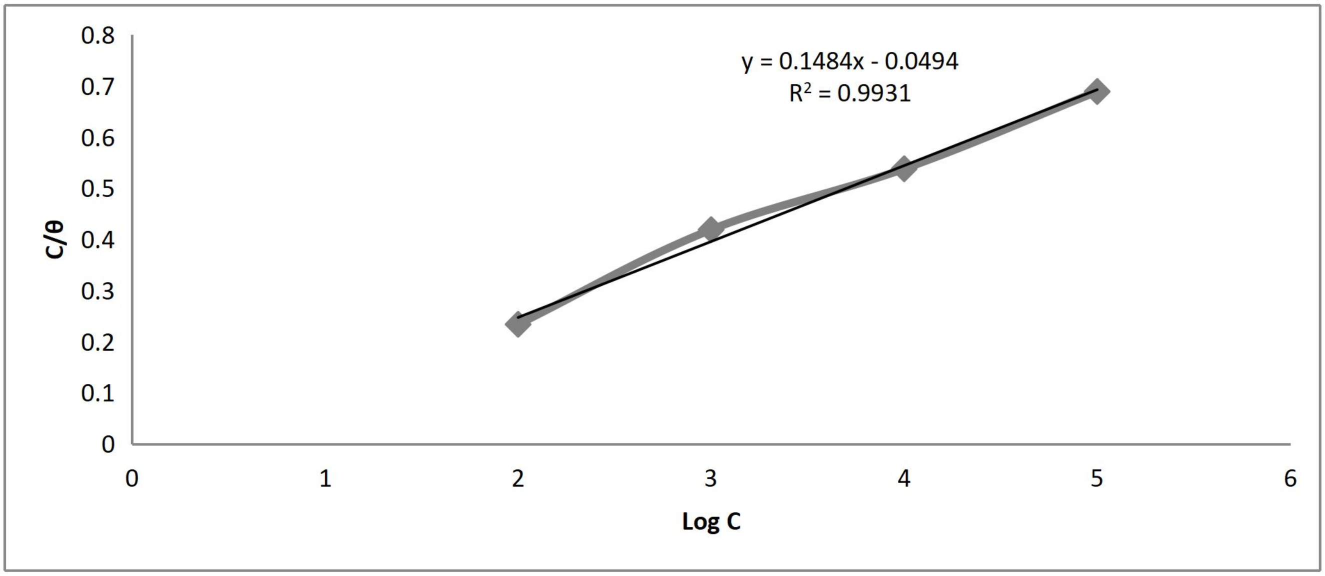

Figure 6: Langmuir Adsorption Isotherm Plot For Corrosion On Mild Steel In *Ficus sur* Extract In 1m HCl At 3hours.

The plots of C/θ against log C gives a straight line plot as seen in Fig 6. This indicates that the adsorption of the inhibitor on the surface of mild steel is in tune with Langmuir isotherm. The correlation coefficient (R^2) value of the adsorption isotherm data obtained was 0.9931, this tells us that Langmuir isotherm is well fitted into this study.

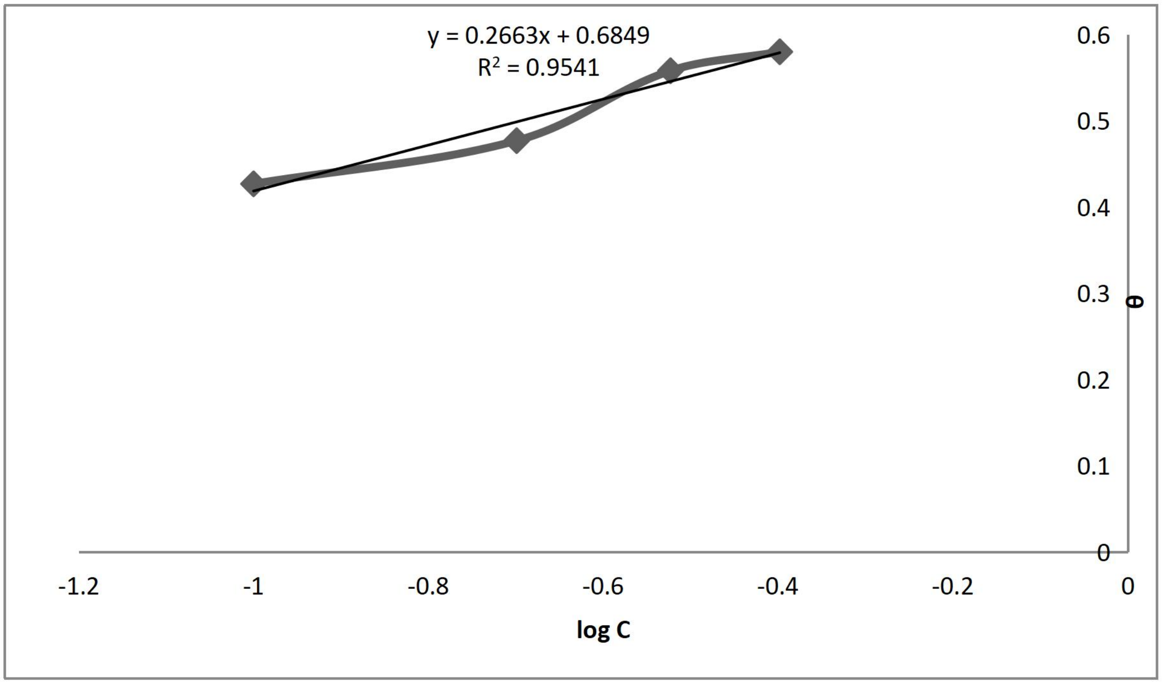

Figure 7: Temkin Adsorption Isotherm Plot For Corrosion Of Mild Steel In Extract Of *Ficus sur* In 1M HCl At 3hours.

A plot of Θ versus IogC (Fig. 7). The Temkin equilibrium adsorption plot correlates with the mild steel and the liquid phase concentration of HCl. The R^2 value obtained from the plot is 0.9541. This is slightly greater than that of Freundlich isotherm.

3.5 EFFECTS OF INHIBITOR CONCENTRATION OF EXTRACT ON INHIBITION EFFICIENCY

Figure 9 shows that inhibition efficiency (IE %) increases with increase in the concentration of the extract. In this study, the inhibition efficiency using 100 mg/L increased from 42.69% to 58 %. In Figure 8, it was observed that corrosion rate decreased with increasing concentration of extract of *Ficus sur.*

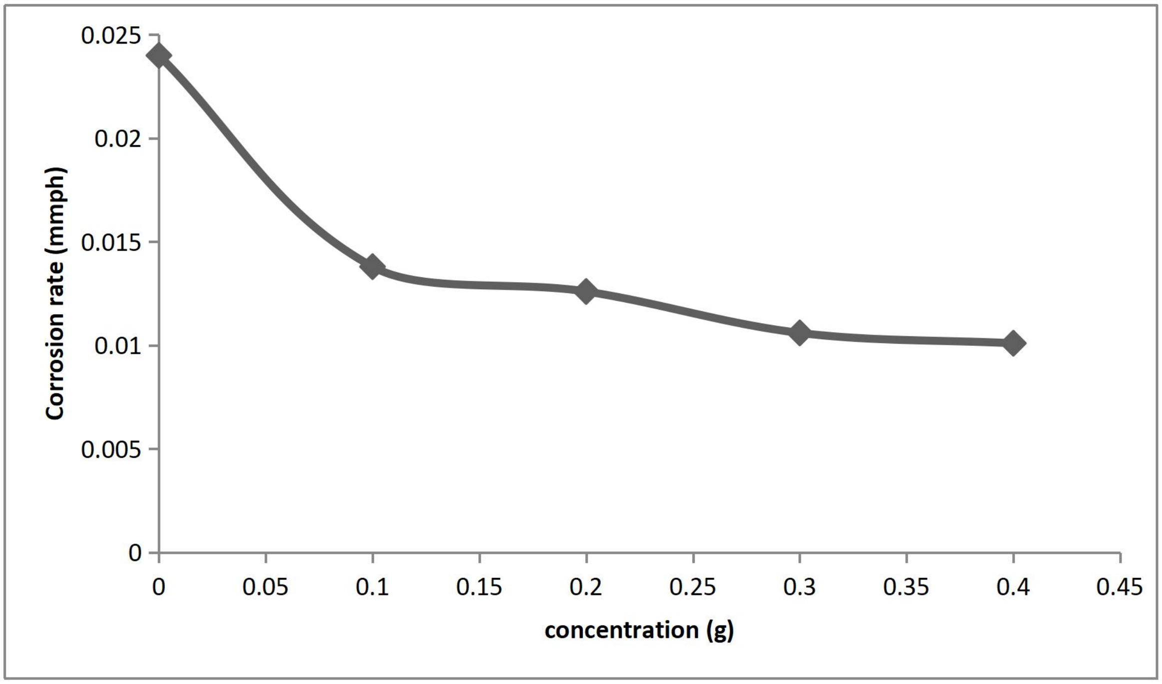

Figure 8: Variation Of Corrosion Rate At Different Concentration

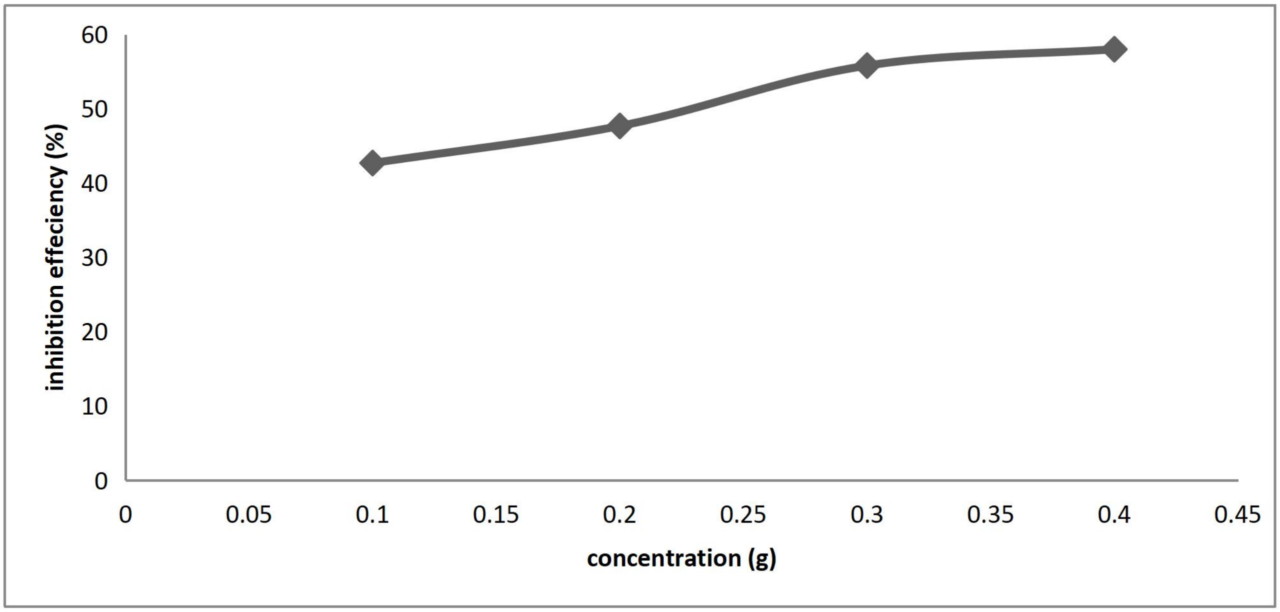

Figure 9: Variation Of Inhibition Efficiency At Different Concentration

Table 3 Correlation coefficient of various adsorption isotherms obtained from *Ficus sur* extract in 1M HCl at 3hours

Adsorption	R^2
Freudlich	0.9508
Temkin	0.9541
Langmuir	0.9931

3.6 PHYTOCHEMICAL SCREENING OF *FICUS SUR* LEAF EXTRACT

The results obtained from the phytochemical screening of *Ficus sur* using qualitative method showed compounds such as alkaloids,glycosides, saponins, and reducing sugars present in the extract are shown in table 4.

CONSTITUENT	**EXTRACT WATER**
Glycoside	+
Saponins	+
Alkaloids	+
Reducing sugars	+

Table 4; Phytochemical Screening Of *Ficus Sur* Leaf Extract

Some studies have reported plants with the phytochemicals: tannin, saponin, phlobatin, terpene, anthraquinone, cardiac glycosides and alkaloids in their extracts as an effective corrosion inhibitor in the acidic environment. Raja, *et al.* The presence of alkaloids saponins compounds normally bring about the formation of film over the surface of the metals, hence causing corrosion inhibition.

The corrosion inhibition of mild steel by *Ficus sur* extracts might be credited to the phyto-constituents of the extract. The presence of π-electrons or the right functional groups like the ketonic, aldehyde, hydroxyl functional group or heterocyclic compound like nitrogen or sulfur e.t.c can rightly ease the movement from the inhibitor's molecule to the metal surface which is equally charged (physisorption) or movement of electron from the inhibitor's molecule to the vacant-orbital of the metal (chemisorption) R.P. Bothi *et al* 2009.

3.7 SEM Analysis of the mild steel

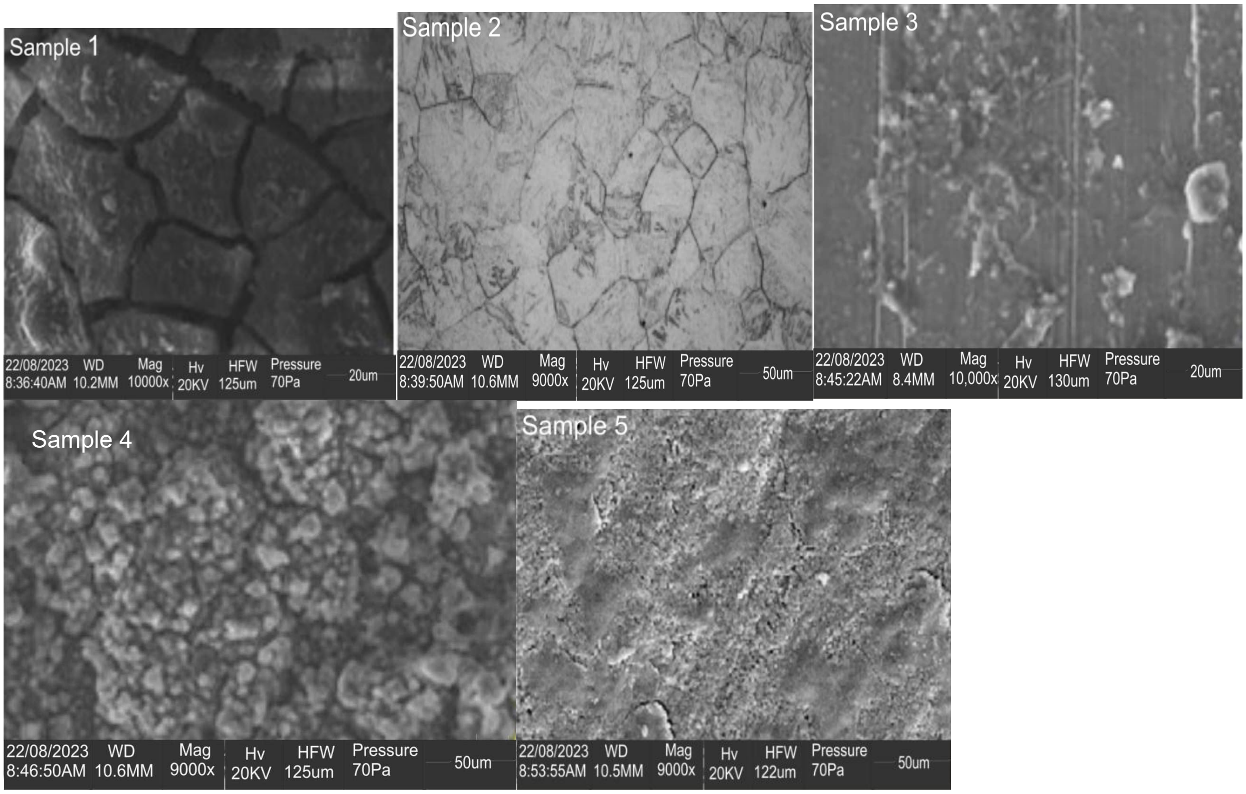

Figure 10. SEM analysis of mild steel at 25^{o}C. Sample 1. without *Ficus Sur* extract and sample 2, 3, 4, and 5 with extract at concentration of 0.1, 0.2, 0.3, and 0.4g

.

Figure 10, revealed SEM analysis of the mild steel surface (at varied inhibitor concentrations) for 25 ◦C corrosion reaction temperatures. From the SEM image, the surface of the mild steel with higher concentration of 0.4 of *Ficus sur* extract is more smother compared with the other surface of lower concentration. That is, increase in *Ficus sur* inhibitor concentration reduced the corrosion rate on the metal surfaces.

CONCLUSION

In conclusion, the study investigated the corrosion inhibition properties of *Ficus sur* as a green inhibitor for mild steel in a 1 M HCl solution at various concentrations (0.1, 0.2, 0.3 and 0.4g). The phytochemical evaluation of water extract of *Ficus sur* implicated the presence of glycosides, alkaloids, saponins and reducing sugars. The results demonstrated the effectiveness of *Ficus sur* in reducing the corrosion rate of mild steel, with inhibition efficiency ranging from 42.69-58.00%. Weight loss measurement and SEM analysis provided valuable insights into the corrosion behavior and surface characteristics of mild steel in the presence and absence of *Ficus sur* extract. The extract's inhibition efficiency rises as the concentration of the inhibitor (extract) is increased and reduces with increasing temperature. The corrosion inhibition is because of the adsorption of the phytochemical components of the extract on the surface of the mild steel which blocked its active sites. The extract was observed to best fit the Langmuir adsorption isotherm. The FT-IR studies showed that the O-H, N-H, C-H and aromatic ring functional groups are present in the extract. This study emphasizes the promising corrosion inhibition properties of *Ficus sur* as a green inhibitor for mild steel in acidic environments. *Ficus sur* effectively reduced the corrosion rate, formed a protective film, and exhibited favorable adsorption characteristics. These attributes make *Ficus sur* a potentially eco-friendly option for corrosion protection in mild steel applications.

RECOMMENDATION

As has been demonstrated in this research, high concentrations of plant-extract-based inhibitors are sometimes required to provide high level inhibition. Although the majority of the plant-extract-based inhibitors provide adequate levels of protection, there is still a need to optimise such formulations. One such way of optimisation is by performing quantum chemical and molecular dynamic simulations to identify the most active ingredient of the various phytochemicals present in a plant extract. The next step of such optimization, is studying the synergism between these active molecules to create an overall superior formulation. Most of the commercial inhibitor formulations are also typically a blend of different chemical compounds.

Future research can delve into understanding the various optimisation of Ficus sur inhibition, evaluating its long-term stability, and assessing its performance under diverse environmental conditions.

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