International Journal of Science, Technology, Engineering and Mathematics
Volume 4 Issue 3 September 2024
DOI: https://doi.org/10.53378/ijstem.353081

Mangifera Indica leaves crude ethanolic extract as a corrosion inhibitor for mild steel in acidic and basic media

[1]John Jeric D. de Castro & [2]Franz Kevin B. Manalo

Abstract

Mild steel corrosion adversely impacts various industries, especially in acidic environments, leading to reduced metal efficiency. This study explored the efficacy of mango leaves crude ethanolic extract (MLCEE) as a natural corrosion inhibitor for mild steel. Different concentrations, such as treatment 1 (25%), treatment 2 (50%), treatment 3 (75%), and treatment 4 (100%) MLCEE, were tested, along with a commercial inhibitor (WD-40). The dilution method was utilized to obtain the concentrations and acid/base solutions. The mild steel plate was cut and pre-treated through rapid thermal annealing. The mild steel was then immersed in 1M HCl and 1M NaOH for its corrosion test. Gravimetric weight loss was computed and statistically analyzed using one-way ANOVA and Tukey's HSD Test to determine the treatments' effectiveness, revealing that the 100% concentration significantly differed from other treatments in both mediums, where it had a p-value of 0.00. Treatment 4 yielded no significant change in the weight of mild steel before (5.05 g) and after (5.01 g) immersion in HCl, and in weight before (4.65 g) and after (4.61 g) immersion in NaOH, as shown in the paired sample t-test, thus it indicates its potential as a metal coating against corrosion activity. This implied that MLCEE is capable of inhibiting corrosion inhibition and can withstand aggressive media. These results may become a basis for future studies covering metal corrosion and plant extract utilization. However, different annealing processes may be considered to promote better adsorption, and other parameters may be added to further explore the efficacy of MLCEE as a potential corrosion inhibitor.

Keywords: *corrosion, mango leaves, natural inhibitor, sodium hydroxide, hydrochloric acid, sustainability, corrosion rate, inhibition efficiency*

Article History:
***Received**: June 10, 2024* ***Revised**: July 18, 2024*
***Accepted**: July 23, 2024* ***Published online**: July 30, 2024*

Suggested Citation:
De Castro, J.J.D. & Manalo, F.K.B (2024). Mangifera Indica leaves crude ethanolic extract as a corrosion inhibitor for mild steel in acidic and basic media. *International Journal of Science, Technology, Engineering and Mathematics*, 4(3), 30-57. https://doi.org/10.53378/ijstem.353081

About the authors:
[1]San Pablo City Science Integrated High School
[2]Corresponding author. Master Teacher I, San Pablo City Science Integrated High School. Email: manalofranzkevin@gmail.com

1. Introduction

Corrosion, a natural process that reduces binding energy in metals and causes oxidation through electron loss, degrades metallic materials via environmental interactions, leading to resource loss, reduced efficiency, and safety risks (Sanni et al., 2019). It shortens structures' lifespans, increasing vulnerability to collapse (Oyekunle et al., 2019). Widely used in manufacturing and industrial sectors for its cost-effectiveness, durability, and hardness, mild steel is prone to easy corrosion in acidic media due to low corrosion resistance, particularly in the presence of hydrochloric acid, posing significant industrial challenges (Habeeb et al., 2018). Corrosion also severely impacts the oil field industry, causing partial and total failures with substantial economic losses (Sanni et al., 2019). Additionally, corrosion greatly affects geothermal plant materials, with the primary risk being corrosion-related failures in processing facilities. Studies in the Philippines, such as the Leyte geothermal field, reveal carbonation decomposes cement paste and lowers concrete pH, accelerating steel bar corrosion, and leading to damage and eventual collapse (Khasani et al., 2021).

Mild steel is widely used in construction due to its low cost and high mechanical strength, but its performance in chemical and electrochemical reactions, especially under acidic and alkaline conditions, limits its application and increases corrosion risk (Oyekunle et al., 2019). A 2013 NACE International study linked the global cost of corrosion, estimated at 3.4% of GDP or $2.5 trillion to $73.5 trillion, to World Bank economic data, highlighting its economic threat. A 2002 USFHWA and NACE study estimated the annual U.S. corrosion cost at $276 billion, or 3.1% of GDP, with nearly half allocated to developing mitigation methods such as corrosion-resistant materials and protective coatings (Mazumder, 2020).

Studies have been published concerning the corrosion in geothermal production facilities in the Philippines, corrosion in the concrete construction of the Leyte geothermal production field is one of them. Carbonation, in addition to decomposing the cement paste, is said to lower the pH of concrete, accelerating the corrosion of reinforcing steel bars in spray tower posts. Furthermore, corrosion on the steel bars used causes damage until the steel breaks and collapses (Khasani et al., 2021).

Corrosion inhibitors are compounds that can stop or slow down the corroding of metal, they can either be inorganic or organic. However, inorganic inhibitors are no longer employed due to their biotoxicity and the presence of dangerous heavy metals (Omran et al., 2022). After the Second Industrial Revolution, the widespread use of chromium and its derivatives as corrosion-preventive compounds accelerated, and such compounds are now ubiquitous in modern society (Gharbi et al., 2018). Thus, this study aimed to evaluate the efficacy of mango (*Mangifera indica*) leaves ethanolic extract on the inhibition of corrosion on mild steel when immersed in acidic and basic media. Certain polyphenols and nutrient groups were highlighted and recognized to have had a significant effect on corrosion inhibition; Pectin, Mangiferin, and Phytochemicals.

The proposed inhibition efficiency of MLCEE was evaluated by varying dilution ratios, which determined the most effective concentration to be used as an alternative to chemical inhibitors. This study aligns with the United Nations Development Program's (UNDP) ninth goal of building resilient infrastructure, promoting sustainable industrialization, and fostering innovation. By emphasizing well-being and safety, the study supports the creation of robust and resilient infrastructure, essential for successful communities. It also aligns with the UNDP's eleventh goal of making cities inclusive, safe, resilient, and sustainable. The study focuses on continuous urban development to achieve these objectives. This study supports the Philippine Development Plan (PDP) by addressing issues related to industry revitalization. By providing information to help manufacturers produce competitive and sustainable products, it advances the PDP’s goals of enhancing research and development, technology, and innovation. This fosters a stronger research culture and productivity, aiding in establishing a competitive research and science industry. Furthermore, the study intersects with the Department of Science and Technology's (DOST) Harmonized National Research and Development Agenda, particularly within the Natural Resources and Environment R&D Agenda. It focuses on the innovative use and monitoring of natural resources to provide lasting solutions to environmental issues, aligning with the agenda's aim to integrate proper functioning and usage of production technologies.

2. Literature Review

2.1 Mango

Recognized as the national fruit of the Philippines, mango holds the status of the third most crucial fruit crop, attributed to its diverse range of applications. Additionally, it is a high-value crop, ranking among the country's leading agricultural export commodities (Jahurul et al., 2015). Data shows that mango production during the previous year was estimated at 596.34 thousand metric tons, with carabao mangoes making up the 83 percent of the whole production (Philippine Statistics Authority, 2023). Mangoes, grown globally for commercial fruit production in tropical and subtropical regions, contain polyphenols, flavonoids, triterpenoids, mangiferin, isomangiferin, tannins, and gallic acid derivatives. Research studies have shown that mangoes offer various potential health benefits, including anti-diabetic, antioxidant, antifungal, antimicrobial, antiviral, hepatoprotective, hypoglycemic, antiallergic, and anti-cancer properties (Parvez & Akanda, 2019). Additionally, mangiferin, a key component of mangoes, exhibits potent anti-lipid peroxidation, immunomodulatory, cardiotonic, wound-healing, and anti-diabetic properties. Mangoes have also been studied for their anti-inflammatory, antiviral, cardiotonic, antioxidant, and anti-diabetic qualities (Hoyos-Arbeláez et al., 2018).

In addition to the economically significant portion (fruit), pruning leaves a large volume of resources such as leaves, stems, and bark, posing disposal challenges for manufacturers. The leaves are one of the possible sources of minerals such as iron, sodium, calcium, magnesium, phosphorus, potassium, nitrogen, and vitamins, to name a few. Mango leaves contain a significant amount of protein. Mango leaves can potentially be used as an alternative source of animal feed in underdeveloped nations to help alleviate livestock food scarcity (Kumar et al., 2021).

2.2 Chemical Properties of Mango Leaves

Previous studies have reported that phytochemicals in the extract, particularly antioxidants, showed inhibition surpassing commercial inhibitors such as Benzohydroxamic Acid (BHA) (Kalisa et al., 2020). The fruit itself has been shown to be a great source of vitamins, phytochemical components, pigments, polyphenolic compounds, and others, demonstrating its potential effectiveness by exhibiting both cathodic and anodic reactions and acting as a mixed-type inhibitor during experimentation (Anupama et al., 2016). Mango leaves contain three types of nutrients: phytochemicals (phenolic, polyphenolic, pigments, and volatile constituents), micronutrients (vitamins and minerals), and macronutrients (carbohydrates, proteins, amino acids, lipids, and organic acids) (Maldonado-Celis et al., 2019).

It is a natural polysaccharide that contains a large amount of poly (D-galacturonic acid), wherein several carboxyl or hydroxyl groups are found within the backbone of the compound while a small percent of its neutral sugars may be present along the side chains. Mango leaves containing 0.39 mg/g of pectin were evaluated to have a significant impact on the corrosive activity of mild steel, as pectin showed an increase in inhibition of 91% within varying temperatures (Fares et al., 2012). Its inhibitory effect is by a protective layer that occasionally forms by the repeating units of the pectin macromolecule containing partially negatively charged oxygen atoms, which when they come into contact with a positively charged metal surface, can encourage electrostatic adsorption. Pectin also displayed adsorption through a coordinate covalent bond between iron and hydroxide molecules (Umoren et al., 2022).

Among its list of phytochemicals, its antioxidant property may come from a xanthone derivative called mangiferin found mainly on its leaves. A C-glucosyl xanthone, mainly from higher plants or vascular plants, confirms that its leaves indeed contain phytochemicals (Ramezanzadeh et al., 2019). Mango leaves contain 0.72 mg/mL of mangiferin, It, along with xanthone, is considered to play a huge part in organ health development, as it is shown to contain properties of anticancer, antidiabetic, and most importantly is an antioxidant. In most known solvents, mangiferin is known to dissolve poorly. However, it dissolves readily in dimethylsulfoxide (DMSO) and dimethylformamide (DMF), and at high concentrations, it can also dissolve in aqueous ethanol. In addition to exhibiting a diverse array of biological behaviors, it occasionally leads to the conventional exploitation of its natural resources. Numerous traditional medical applications have been documented for plants containing even trace amounts of mangiferin. Previous practical scientific studies have confirmed some of these therapeutic effects' potential (Rao et al., 2023).

2.3 Mild Steel

Mild steel, also known as low or plain-carbon steel, is one of the most commonly used types of steel in manufacturing due to its relatively cheap cost and its material properties which are suitable for a wide range of applications (Singh et al., 2016). However, despite its adaptability, it has its disadvantages, such as its low resistance against corrosion under very harsh environments. Moreover, the use of hydrochloric acid in cleaning, descaling, pickling, and oil well acidizing, causes severe corrosion attacks on mild steel (Chellouli et al., 2016). Resulting in an increase in human safety risks due to its poor corrosion resistance despite its widespread use in a variety of industries. Steel is known to have very weak resistance to corrosion which causes mild steel to corrode easily and lose its mechanical strength as the acidic media affects its microstructure (Habeeb et al., 2018). This happens due to the absence of a chromium oxide protective layer (Cr2O3), which produces a hard surface on mild steel, which prevents its iron content from reacting to oxygen (Yu et al., 2018). With its absence, oxidation tends to occur as the iron reacts with water and oxygen to produce hydrated iron (III) oxide, which has a reddish flaky appearance, which we know as rust, and would worsen over time (Srivastava et al., 2016).

2.4 Rapid Thermal Annealing

RTA commonly includes lamps are used to heat a substrate quickly to high temperatures to promote a rapid reaction in the cold-wall reactor, such as rapid deposition (RTP-CVD), annealing (RTA), oxidation (RTO), reflow, diffusion, and film reaction. This method includes the substrate to be rapidly heated at a high temperature and then cooled down. The rapid exposure to a high temperature is sufficient to achieve the desired objective of annealing but not too long to damage the sensitive parts of the substrate (Najafi et al., 2016). A study by Rashid et al. (2013) showed that RTA had a positive effect on the structural and thermoelectric properties of bismuth telluride films. Tests such as SEM imaging and thermoelectric measurements showed improvement within the thermoelectric properties of the steel that could be attributed to microstructural changes due to the rapid thermal annealing treatment.

2.5 Corrosion Inhibition

Corrosion inhibition from the addition of corrosion inhibitors and corrosion inhibition from components included in crude oil are the two most prominent sources to take into account (Zarras & Stenger-Smith, 2015). Past studies suggest that temperature and pressure typically deteriorate the corrosion and pitting resistance of most alloys. However, alloys such as AMCs (Aluminum Matrix Composites) maintain superior pitting resistance even under high temperature and pressure conditions, with hydrostatic pressure having little effect on their pitting resistance (Sun et al., 2023). Using either inorganic or organic pretreatment techniques is often discussed, and a comprehensive review of corrosion inhibition on a range of metals and alloys has been provided. Corrosion inhibitors are one of the most efficient and economical corrosion control techniques for shielding metals from corrosion in acidic environments due to the aggressive nature of acid solutions. Excellent anti-corrosive properties have been found for corrosion inhibitors in the past. A noticeable portion of them had unfavorable environmental side effects. Research on inhibitors that are safe for the environment, like organic inhibitors, is therefore still ongoing (Nešić et al., 2017).

Chemisorption is a type of adsorption where chemical bonds hold the material that has been adsorbed together. Only when a chemical bond forms between the adsorbent and the adsorbate can chemisorption take place, and it has a high specificity. The surface area determines the rate of chemisorption (Shanmugam et al. 2023). According to Thakur et al. (2022), chemisorption rises as the adsorbent's surface area increases. It happens when there are robust interactions between the adsorbate and the solid surface, such as hydrogen bonding and the formation of covalent and ionic bonds.

2.6 Sodium Hydroxide

Sodium Hydroxide (NaOH) is an inorganic compound that is also referred to as Lye or Caustic Soda. The hydroxide anions (OH-) and sodium cations (Na+) make up this potent soluble base. It is frequently found in household products such as alkaline batteries, paint and varnish removers, drain cleaners, oven cleaners, degreasing agents, automatic dishwasher detergents, and bleach stabilizers. (Gad, 2024). Sodium hydroxide can lead to a particular kind of corrosion known as stress corrosion cracking (SCC) or caustic embrittlement at high concentrations. This kind of corrosion is frequently unpredictable and can have disastrous consequences if ignored. The majority of the steel's surface remains unaffected during this time, but surface cracks start to form and widen. The disintegration of the passive layer on a metal surface in SCC is typically attributed to mechanical causes because stress must be applied. Many theories, including those involving film mechanical breakdown, passivation, damaging species adsorption, hydrogen embrittlement, and electrochemical dissolution, have been put forth to explain SCC (Saha, 2016).

2.7 Hydrochloric Acid

Hydrochloric acid (HCl), also known as muriatic acid or spirits of salt, is an inorganic chemical that is typically colorless and has a pungent smell. It is where hydrogen chloride is dissolved in an aqueous solution with water (Benvenuto, 2015). Because of its corrosive nature, the Environmental Protection Agency (EPA) classified hydrogen chloride (HCl) as a toxic substance at concentrations of 37% and higher. In the hydrochloric acid system, the majority of common metal materials experience severe activation corrosion (Brandt et al., 2017). The rate of corrosion increases noticeably as the hydrochloric acid's concentration and temperature rise. Furthermore, because of the abundance of extremely active chloride ions in the hydrochloric acid medium, the passivation film on the metal material's surface can be destroyed, leading to complete material corrosion as well as stress corrosion, pitting corrosion, and cracking of stainless steel and many other metals (Fan et al., 2021).

2.8 Ethanolic Extraction

Glycosides, polyacetylenes, polyphenols, sterols, tannins, flavonols, terpenoids, and alkaloids can all be drawn to ethanol (Azmir et al., 2013). One of a class of chemical compounds known as alcohols is ethanol (ethyl alcohol, CH_3CH_2OH), which is made up of molecules that have an OH group attached to a carbon atom. As a solvent for natural ingredients used in food and natural medicine, ethanol is safe for human consumption (Alam & Tanveer, 2020). Phenolic derivative antioxidant compounds have been successfully extracted from natural ingredients using both absolute and aqueous ethanol (Lusiana et al., 2021).

3. Methodology

3.1 Collection and Extraction of MLCEE

The mango leaves were obtained from a fellow researcher's tree located in Barangay San Miguel, San Pablo City. To ensure their safety and suitability for experimentation, the leaves underwent examination for pests and usability, followed by washing with distilled water and drying under direct sunlight. For the extraction of the mango leaves' crude ethanolic extract, a total of 3.281 kilograms of leaves were sent to the University of the Philippines Los Baños Institute of Chemistry Analytical Sciences Laboratory (UPLB IC-ASL) for necessary procedures. The leaves were air dried for 3 days, then oven dried at 40°C for about 24 hours to ensure full drying, given their 80% water content, followed by grinding into a fine powder using a Wiley mill. An 80% (v/v) ethanol solvent was prepared in advance, and 100ml of this solvent was mixed with 200g of ground mango leaves for maceration over 48 hours. After maceration, the solution was filtered through cheesecloth and Whatman #1 to remove impurities. Subsequently, it underwent rotary evaporation for 2 hours at 40°C and 0.09MPa to distill the ethanol, before being transferred to an amber bottle and stored in the refrigerator until needed.

Each treatment and replicate were prepared using the dilution method, it was used to determine the ratio between the stock solution and solvent, where the MLCEE pure extract served as the stock solution, and distilled water served as a solvent to create the treatments.

$$\mathbf{C_1V_1 = C_2V_2}$$

$\mathbf{C_1}$ = concentration of the stock solution (mL), $\mathbf{V_1}$ = volume of extract in each treatment (mL), $\mathbf{C_2}$ = Concentration of each treatment (%), $\mathbf{V_2}$ = volume of the treatment (mL)

The obtained mango leaves aqueous extract was diluted with different amounts of water to produce varying concentrations of 25%, 50%, 75%, and 100% (Gitahi et al., 2021). Table 1 displays how the MLCEE is distributed in relation to water.

Table 1

Varying concentrations of MLCEE in water

Treatments	Concentration
1	25%: 2.5mL MLCEE stock solution mixed in 7.5mL water
2	50%: 5mL MLCEE stock solution mixed in 5mL water
3	75%: 7.5mL MLCEE stock solution mixed in 2.5mL water
4	100%: 10mL MLCEE stock solution mixed in 0mL water
5	10mL of chemical inhibitor (Positive Control)
6	10mL of water (Negative Control)

3.2 Steel Preparation and Annealing

The mild steel sheet was cut at approximately 1cm × 1cm × 0.5cm (Dominic & Monday, 2016), and polished with emery paper with the grade numbers 100, 320, 400, and 600 to get the desired shiny and polished surface (Khodair et al., 2019). The steel was submerged in an acetone solution to clean the excess dirt and oil remaining on its surface, and then washed with room-temperature distilled water and air-dried (Muthukrishnan et al., 2017).

It was then pre-treated using a rapid thermal annealing process (RTA), a temperature of more than 1100°C using a butane torch was put over the substrates for about 30 seconds (Jandaghi et al., 2021). It was then put in a zip-lock bag until its presence was needed. Its initial weight was taken using an electronic weighing scale.

3.3 Arrangement of Experimentation Set-up

This study made use of a True Experimental Research Design that utilized a Completely Randomized Research Design (CRD), two set-ups were made to satisfy the research design, one for the experimental group and the other for the control group. The experimental group has one trial and three replicates of each varying concentration. The trials and replicates were randomized in a way where each treatment had an equal chance of receiving treatment (Sekhar et al., 2019). Each set-up containing mild steel sheets ended up having an equal chance of receiving any given treatment. It ensures that any remaining error in the measurements is completely random and supports the claim that the measurements are accurate and precise.

3.4 Testing Procedure

Different concentrations of MLCEE were tested to identify its effectiveness against corrosion, using the gravimetric method to determine the mean weight, corrosion rate, and inhibition efficiency of each experimental group. The research involved testing varying ratios of MLCEE through laboratory methods such as gravimetric (weight loss) measurement, rapid thermal annealing, and crude ethanolic extraction. The study employed statistical tests using Microsoft Excel, including one-way ANOVA and Tukey's HSD, to analyze to resulting mean weight, corrosion rate, and inhibition efficiency.

Formulation of Acidic and Basic Media. The base or Sodium Hydroxide solution in which the mild steel was put for corrosion testing was obtained by mixing 40 grams of NaOH and 1000 mL of distilled water to get the desired 1M concentration of the NaOH solution (Ekeke et al., 2020).

The Acid or Hydrochloric acid solution in which the mild steel was put for corrosion testing was obtained by mixing 83 ml of pure HCl and 1000 mL of distilled water to get the desired 1M concentration of HCl solution (Ramezanzadeh et al., 2019).

These amounts of pure acid and base solutions are in correlation to the dilution method, where the before-and-after concentrations and volume of substances can be related to getting the precise amount of solute and/or solvent. The equation is as follows;

$$\mathbf{M_1V_1 = M_2V_2}$$

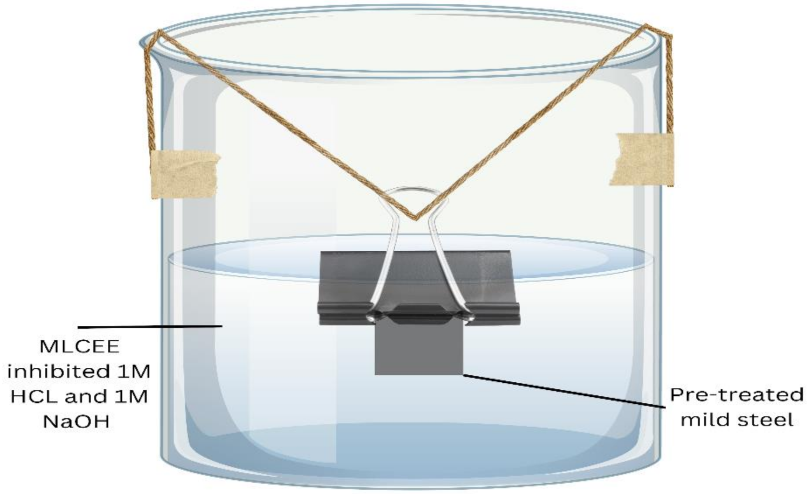
$\mathbf{M_1}$ = Initial molarity (M), $\mathbf{V_1}$ = initial volume (L), $\mathbf{M_2}$ = Final Molarity (M), $\mathbf{V_2}$ = Final Volume (L)

The hydrochloric acid and sodium hydroxide were diluted using a copious amount of water and disposed of by drain discharge as both of the mediums had a concentration of 1 mol/L or 1M, which is labeled as a dangerous substance.

Steel Immersion. The pre-treated mild steel sheets were then immersed in a beaker containing 1M HCl in the absence and presence of different concentrations of MLCEE (25%, 50%, 75%, 100%) for 24 hours. After a period of 24 hours, the corroded mild steel substrates were withdrawn from the acid, immersed in muriatic acid for 20 seconds to remove the remaining corrosive product oxide within the metal, thoroughly washed with acetone, then rinsed with distilled water, and sun-dried. The substrate was then weighed for its final weight. It was then weighed using an electronic weighing scale for its final weight. Figure 1 depicts how the mild steel is submerged in the NaOH solution and HCl.

Figure 1

Mild steel as submerged in MLCEE inhibited and uninhibited acidic and basic media for the Test of Corrosion



4. Findings and Discussion

4.1 Comparable Qualities of Each Treatment Immersed in HCl

Table 2

Mean weights of each treatment immersed in 1M HCl medium at varying concentrations

Treatments	Mean Initial Weight	Mean Final Weight	Mean Weight Loss
25% (1mL/3mL)	4.47 g	4.1 g	0.37 g^{c}
50% (2mL/2mL)	5.4 g	5.07 g	0.33 g^{c}
75% (3mL/1mL)	4.67 g	4.54 g	0.13 g^{b}
100%(4mL/0mL)	5.05 g	5.01 g	0.04 g^{a}
Positive Control	4.21 g	4.14 g	0.08 g^{ab}
Negative Control	4.85 g	4.3 g	0.55 g^{a}

Note: Data are means of three replicates. The means of the same letter are not significantly different.

Statistical differences were determined using one-way ANOVA ($p<0.05$) followed by a post-hoc test, Tukey's HSD.

Table 3 displays the mean initial weight, final weight, and weight loss of mild steel exposed to varying concentrations in an HCl medium. In the absence of the inhibitor, the weight loss reaches its maximum with a mean of 0.55 g. Conversely, the highest concentration (100%, 10 mL/0 mL) yields the lowest average weight reduction of 0.04 g, comparable to the positive control's result of 0.08 g. Furthermore, Tukey's HSD test highlights the significance of treatment 4 compared to treatment 5, suggesting the potential of the pure extract to rival a commercial inhibitor. This treatment also significantly differs from the negative control and other experimental setups, exhibiting the lowest mean weight loss.

Table 3

Test of differences between the mean initial and final weight of each treatment immersed in HCl

Treatments	t	Sig.	Verbal Interpretation
25% (1mL/3mL)	13.109	0.006	significant
50% (2mL/2mL)	14.945	0.004	significant
75% (3mL/1mL)	14.363	0.005	significant
100%(4mL/0mL)	4.158	0.053	not significant
Positive Control	6.379	0.024	significant
Negative Control	27.29	0.001	significant

Table 3 presents the paired sample t-test results of each treatment's mean initial and final weights. Treatments 1 (2.5mL/7.5mL), 2 (5mL/5mL), and 3 (7.5mL/2.5mL), as well as the positive and negative control, showed significance before and after MLCEE treatment application. Conversely, treatment 4 (10mL/0mL) was deemed insignificant in weight difference pre- and post-MLCEE application. This statistical analysis underscores visible changes in mild steel weight with MLCEE application at certain concentrations, with treatment 4 exhibiting the lowest weight loss, indicating its corrosion inhibition capability.

Table 4

Test of difference in weight loss of each treatment in HCl

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.615	5	0.123	127.2	0.00
Within Groups	0.012	12	0.001		
Total	0.626	17			

***Note**:* *p<0.05 significant; p>0.05 not significant

Table 4 displays the results of a one-way ANOVA and Tukey’s HSD test on the weight loss of each treatment immersed in NaOH. The p-value of 0.00, falling below the desired threshold of $p<0.05$, signifies significance, leading to the rejection of the null hypothesis. Supported by an f-value of 127.2, which exceeds 1, further confirming the rejection of the null hypothesis. Among the treatments, Treatment 4 (100% concentration) achieved the lowest and most desirable result of 0.04, comparable to the positive control (chemical inhibitor), indicating its potential to match known commercial inhibitors.

Figure 2

Mean corrosion rate of each treatment immersed in 1M HCl

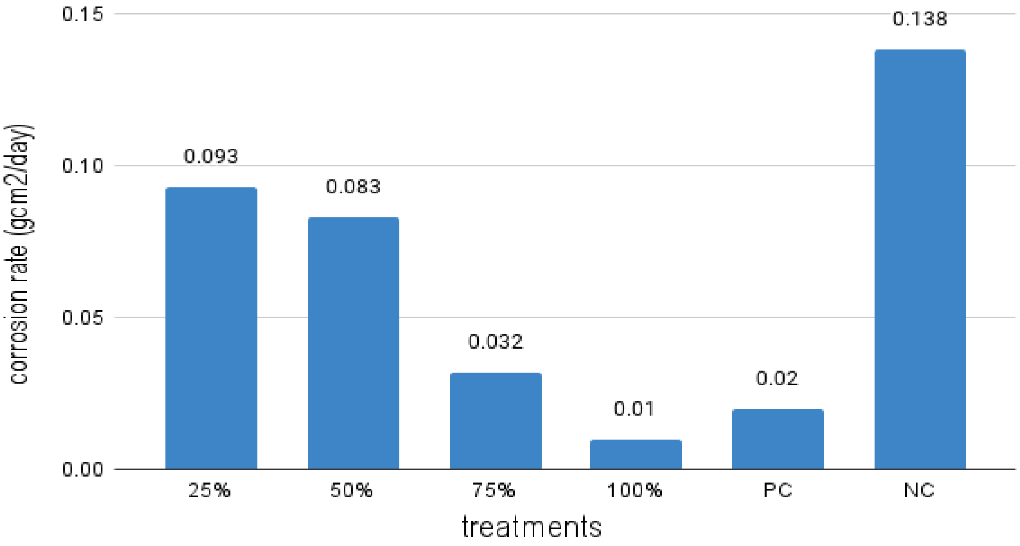


Figure 2 illustrates the corrosion rate of each treatment using the gravimetric weight loss method. Treatment 1 (2.5ml/7.5ml) exhibited the highest corrosion rate at 0.093, while treatment 4 (10ml/0ml) demonstrated the lowest corrosion rate at 0.01. An inverse relationship between corrosion rate and concentration is evident, indicating that as concentrations increased, corrosion rates decreased. This suggests that the purity of the extract, in terms of dilution, influences its effectiveness, with 100% concentration yielding the most favorable results and 25% showing the least favorable outcomes. These variations in corrosion rates among treatments suggest that the application of different concentrations of MLCEE induces changes in mild steel corrosion.

Figure 3

Mean inhibition efficiency of each treatment immersed in 1M HCl

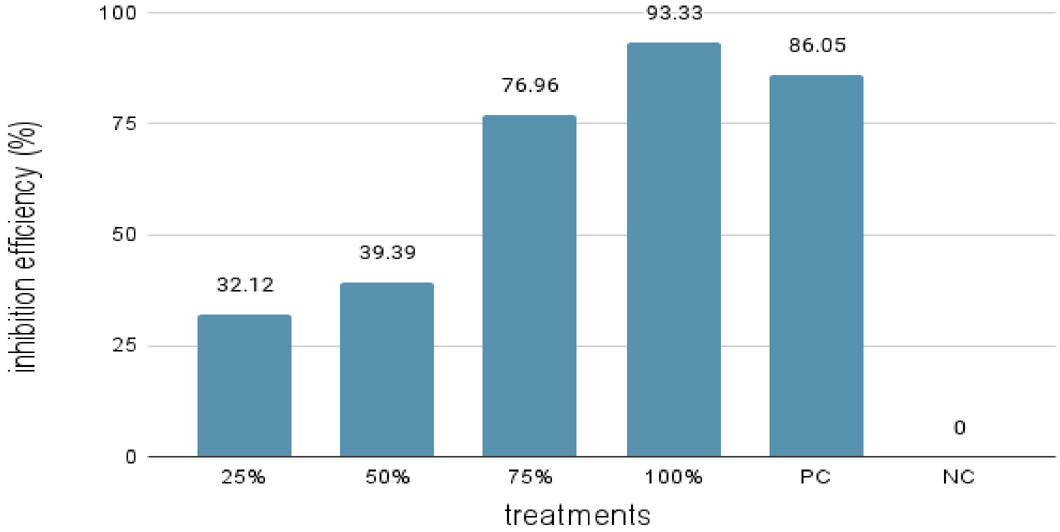


Figure 3 displays the inhibition efficiency of each treatment using the gravimetric weight loss method. Treatment 4 (10ml/0ml) exhibited the highest inhibition percentage at 93.33%, while treatment 1 (2.5ml/7.5ml) showed the lowest inhibition percentage at 32.12%. A direct relationship between inhibition efficiency and concentration is evident, indicating that as concentrations increased, inhibition percentages also increased. This suggests that the extract's effectiveness is influenced by its purity through dilution. Treatment 4 (10ml/0ml) generated the most favorable results, whereas treatment 1 (2.5ml/7.5ml) produced the least favorable outcomes. These findings imply that applying different concentrations of MLCEE to the treatments led to variations in mild steel inhibition.

4.2 Comparable Qualities of each treatment immersed in NaOH

Table 5

Mean weights of each treatment immersed in 1M NaOH medium at varying concentrations

Treatments	Mean Initial Weight	Mean Final Weight	Mean Weight Loss
25% (2.5mL/7.5mL)	5.12 g	4.81 g	0.31 g^{c}
50% (5mL/5mL)	4.25 g	4.1 g	0.15 g^{b}
75% (7.5mL/2.5mL)	5.52 g	5.38 g	0.14 g^{b}
100%(10mL/0mL)	4.65 g	4.62 g	0.04 g^{a}
Positive Control	4.61 g	4.57 g	0.04 g^{a}
Negative Control	4.48 g	4.12 g	0.36 g^{c}

Note: Data are means of three replicates. The means of the same letter are not significantly different.

Statistical differences were determined using one-way ANOVA ($p<0.05$) followed by a post-hoc test, Tukey's HSD.

Table 5 displays the mean initial weight, final weight, and weight loss for mild steel exposed to various concentrations in a NaOH medium, revealing that the absence of the inhibitor results in maximum weight loss at an average of 0.36 g, while the 100% concentration (10 mL/0 mL) achieves the lowest average weight reduction of 0.04 g, resembling outcomes of the positive control. Additionally, Tukey's HSD test underscores treatment 4's significance compared to treatment 5, indicating the potential of the pure extract to rival the commercial inhibitor, with treatment 4 exhibiting the lowest mean weight loss.

Table 6

Test of differences between the mean initial and final weight of each treatment immersed in HCl

Treatments	t	Sig.	Verbal Interpretation
25% (1mL/3mL)	12.318	0.007	significant
50% (2mL/2mL)	11.5	0.007	significant
75% (3mL/1mL)	6.143	0.025	significant
100%(4mL/0mL)	4.158	0.053	not significant
Positive Control	13	0.006	significant
Negative Control	15.571	0.004	significant

Table 6 presents the results of a paired sample t-test comparing the mean initial and final weights for each treatment. Treatments 1, 2, and 3, along with the positive and negative controls, showed significance both before and after the MLCEE application. Conversely, treatment 4 displayed insignificance in weight change before and after MLCEE administration. However, in this statistical analysis emphasizing differences, significance suggests that MLCEE application at specific concentrations led to observable changes in mild steel weight. Notably, treatment 4 exhibited the least weight loss, indicating its effectiveness in corrosion inhibition.

Table 7

Test of difference in weight loss of each treatment in NaOH

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.275	5	0.055	55.291	0.00
Within Groups	0.012	12	0.001		
Total	0.287	17			

Legend: *p<0.05 significant; p>0.056 not significant

Table 7 displays the results of one-way ANOVA and Tukey's HSD test on the weight loss of each treatment immersed in NaOH, revealing significant similarities among treatments and their respective replicates with a p-value of 0.00, supporting the rejection of the null hypothesis. This aligns with the data, showing close resemblances within a narrow window of 0.1-0.2 g, with Treatment 4 (100%) yielding the most favorable results at 0.04 g, indicating a substantial impact on mild steel's corrosive activity.

Figure 4

Mean corrosion rate of each treatment immersed in 1M NaOH

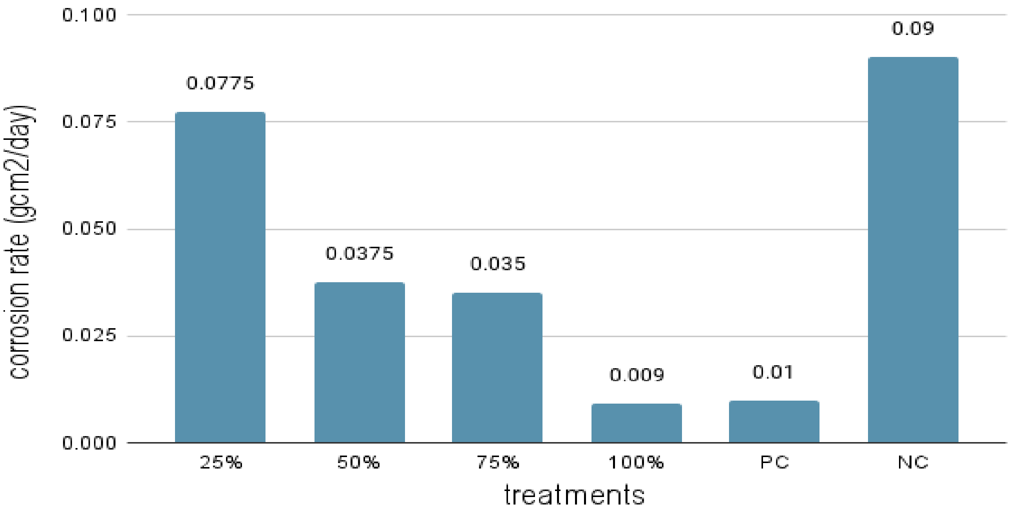


Figure 4 illustrates the corrosion rate of each treatment using the gravimetric weight loss method. Treatment 1 (2.5ml/7.5ml) exhibited the highest corrosion rate at 0.0775, while treatment 4 (10ml/0ml) demonstrated the lowest corrosion rate at 0.009. An inverse relationship between corrosion rate and concentration is evident, indicating that as concentrations increased, corrosion rates decreased, suggesting that the purity of the extract, in terms of dilution, influences its effectiveness. Treatment 4 (10ml/0ml) yielded the most favorable results, while treatment 2 (2.5ml/7.5ml) produced the least favorable outcomes, implying that applying various concentrations of MLCEE induced changes in mild steel corrosion.

Figure 5

Mean inhibition efficiency of each treatment immersed in 1M NaOH

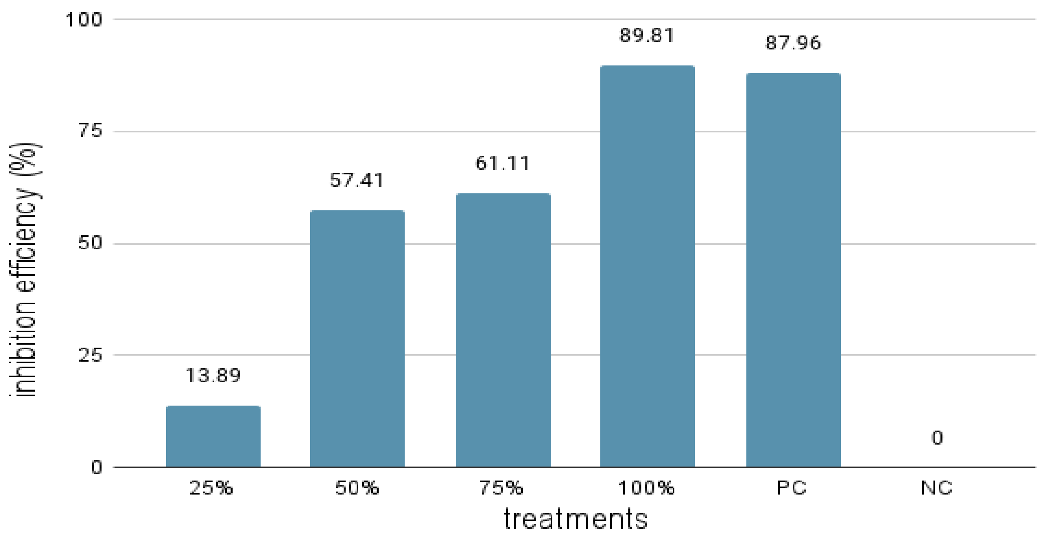


Figure 5 illustrates the inhibition efficiency of each treatment using the gravimetric weight loss method. Treatment 4 (10ml/0ml) exhibited the highest percentage of inhibition at 89.81%, while treatment 1 (2.5ml/7.5ml) showed the lowest inhibition percentage at 13.89%. A direct relationship between inhibition efficiency and concentration is evident, indicating that as concentrations increased, inhibition percentages also increased, suggesting that the extract's effectiveness is influenced by its purity concerning dilution. The graph highlights that the 100% concentration produced the most favorable results, while the 25% concentration yielded the least favorable outcomes, suggesting that applying different concentrations of MLCEE to the treatments resulted in variations in mild steel inhibition.

5. Conclusion

The study investigated the corrosive behavior of mild steel in 1M HCL and 1M NaOH solutions with varying concentrations of mango leaves aqueous extract (MLCEE). Results from the Gravimetric (Weight Loss) Measurement Method indicated that a 100% concentration of MLCEE effectively minimized mild steel weight loss in both acidic and basic mediums, with a mean loss of 0.04 g. Paired t-test analysis revealed significant differences pre- and post-application of MLCEE in the 100% concentration and positive control groups, while no significant differences were observed in the 50%, 75%, and negative control groups. Furthermore, corrosion rate tests showed that the 100% concentration exhibited the lowest corrosion rates, indicating superior effectiveness. Additionally, at 100% concentration, inhibition efficiency reached maximum values of approximately 93.33% in acidic and 89.81% in basic solutions after 24 hours of immersion, confirming that it contains phytochemical compounds such as mangiferin and pectin with inhibitory potential. These compounds form a protective film on mild steel surfaces, inhibiting the formation of iron oxides and blocking cathodic reactions, thereby preventing corrosion. Hence, the MLCEE acted as a mixed-type inhibitor, demonstrating both anodic and cathodic reactions.

In conclusion, the study showed that mango leaves' crude ethanolic extract can be used as a natural corrosion inhibitor for mild steel to prevent it from corroding easily when exposed to an acidic environment. Along with the data presented, this study also indicates that MLCEE is able to compete with the results of the chemical inhibitor. these results may become the basis for manufacturers and allied industries towards their goal of sustainable development and communities. Though limitations were observed, this study may serve as a starting point to explore further knowledge in creating an alternative inhibitor that is safer and more cost-effective and corrosion inhibition that is safer and more accessible for real-life scenarios.

The results are due to the presence of aromatic rings (arenes), carbonyl (C=O), hydroxyl (-OH), and carboxylic ($R-CO_2H$) functional groups within the coating of MLCEE on mild steel, compounds mentioned play a big role in the absorbance ability of MLCEE, as electron exchange is able to happen that eventually creates a bond between the inhibitor and extract. These functional groups may be traced in the structures of the compounds existing in polyphenolic groups from the extract, such as gallic acid, mangiferin, and pectin (Ramezanzadeh et al., 2019).

Due to the dissolution of iron atoms when immersed in the 1M NaOH, the oxide film dissolves during the immersion time. After 24 hours of immersion, 100% concentration yielded the least amount of weight loss, corrosion rate, and inhibition efficiency, this indicates that a passivation layer formed and inhibited corrosion. The decrease in corrosion rate and increase in inhibition efficiency as the extract concentration increases may be related to the stability of the passive layer that formed on the steel surface through chemisorption. While 25% yielded the least favorable results of 0.31 g of weight loss, 0.0775 (g/cm2day) in corrosion rate, and 13.88% in inhibition efficiency. The increase in corrosion rate and decrease in inhibition efficiency indicates that the NaOH was able to penetrate through the porosity of the MLCEE and reach the steel surface.

In addition, these positive results may be connected to the heteroatoms, such as N, S, and O, present within the aromatic groups of the MLCEE. The availability of these heteroatoms promotes better adsorption with the steel surface, which then leads to better results in inhibition efficiency as shown in the 100% concentration (Quraishi et al., 2021). Along with the heteroatoms, the polar heterosides and hydroxyl groups that are present with the MLCEE enhance the adsorption of the heteroatoms, which then leads to inhibition property as shown with the treatments. The adsorption of these heteroatoms results in the formation of an interface barrier between the metal-electrolytes which prevents any interaction between the basic medium and limits corrosion (Da Rocha et al., 2014).

Though limitations were observed, this study may serve as a starting point to explore further knowledge in creating an alternative inhibitor that is safer and more cost-effective and corrosion inhibition that is safer and more accessible for real-life scenarios. For future studies, incorporating additional surface characterization techniques, such as Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS), and X-ray Photoelectron Spectroscopy (XPS), would be beneficial to confirm the presence and uniformity of the protective film formed by MLCEE on the steel surface. Studies may also tackle the long-term stability of the extract to test its effectiveness over extended periods of time. Furthermore, the cost-effectiveness of using the MLCEE may be studied further to provide more basis on an industrial aspect.

Acknowledgment

The authors would like to express their sincere gratitude to Dr. Ma. Ruby A. Mendoza, School Head of San Pablo City Science Integrated High School, for authorizing the conduct of the research study and allowing it to be part of the school’s legacy for future academic use; to Engr. Romelyn Ariadna Minorka R. Itong of San Pablo City Science Integrated High School, for supervising the researchers during experimentation, helping them to pursue the goals of the study; and to the University of the Philippines Los Baños –

Institute of Chemistry for allowing the researcher to utilize their services and providing a detailed background of the necessary practices.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was not supported by any funding.

References

Alam, M. S., & Tanveer, M. S. (2020). Conversion of biomass into biofuel: a cutting-edge technology. *Elsevier eBooks* (pp. 55–74). https://doi.org/10.1016/b978-0-12-821264-6.00005-x

Ali, N., & Fulazzaky, M. A. (2020). The empirical prediction of weight change and corrosion rate of low-carbon steel. *Heliyon*, *6*(9), e05050. https://doi.org/10.1016/j.heliyon.2020.e05050

Anupama, K., Ramya, K., & Joseph, A. (2016). Electrochemical and computational aspects of surface interaction and corrosion inhibition of mild steel in hydrochloric acid by Phyllanthus amarus leaf extract (PAE). *Journal of Molecular Liquids*, *216*, 146–155. https://doi.org/10.1016/j.molliq.2016.01.019

Benvenuto, M. A. (2015). Industrial inorganic chemistry. *De Gruyter eBooks*. https://doi.org/10.1515/9783110330335

Brandt, M. J., Johnson, K. M., Elphinston, A. J., & Ratnayaka, D. D. (2017). Chemical storage, dosing and control. *Elsevier eBooks* (pp. 513–552). https://doi.org/10.1016/b978-0-08-100025-0.00012-0

Chellouli, M., Chebabe, D., Dermaj, A., Erramli, H., Bettach, N., Hajjaji, N., Casaletto, M., Cirrincione, C., Privitera, A., & Srhiri, A. (2016). Corrosion inhibition of iron in acidic solution by a green formulation derived from *Nigella sativa* L. *Electrochimica Acta*, *204*, 50–59. https://doi.org/10.1016/j.electacta.2016.04.015

Da Rocha, J.C, Da Cunha Ponciano Gomes, J.A., & D'Elia, E. (2014). Aqueous extracts of mango and orange peel as green inhibitors for carbon steel in hydrochloric acid solution. *Materials Research: American Journal of Materials 17*(6), 1581–87. https://doi.org/10.1590/1516-1439.285014

Dominic, O., & Monday, O. (2016). Optimization of the inhibition efficiency of mango extract as corrosion inhibitor of mild steel in 1.0M H_2 SO_4 using response surface methodology. *Journal of Chemical Technology and Metallurgy* 51 (3), 302–14.

Ekeke, I. C., Olubiyi S. O., Obasi, E. E., Nzeoma, C., Anyikwa, S. O., Uzoma, H. C & Ngolube, B. C. (2020). Investigation of the inhibitive properties of *Mangifera indica* (Mango) seed extract on aluminum metal corrosion in 0.5m HCl medium. *International Journal of Engineering Applied Science and Technology*, *5*(4), 515–520. https://doi.org/10.33564/ijeast.2020.v05i04.081

Fan, R., Zhang, W., Wang, Y., Chen, D., & Zhang, Y. (2021). Metal material resistant to hydrochloric acid corrosion. *Journal of Physics. Conference Series*, *1732*(1), 012134. https://doi.org/10.1088/1742-6596/1732/1/012134

Fares, M. M., Maayta, A., & Al-Qudah, M. M. (2012). Pectin as promising green corrosion inhibitor of aluminum in hydrochloric acid solution. *Corrosion Science*, *60*, 112–117. https://doi.org/10.1016/j.corsci.2012.04.002

Fayomi, O. S. I., & Popoola, A. P. I. (2019). Corrosion propagation challenges of mild steel in industrial operations and response to problem definition. *Journal of Physics. Conference Series*, *1378*(2), 022006. https://doi.org/10.1088/1742-6596/1378/2/022006

Gad, S. E. (2024). *Lye*. *Elsevier eBooks* (pp. 997–1001). https://doi.org/10.1016/b978-0-12-824315-2.00905-2

Gharbi, O., Thomas, S., Smith, C., & Birbilis, N. (2018). Chromate replacement: what does the future hold? *NPJ Materials Degradation*, *2*(1). https://doi.org/10.1038/s41529-018-0034-5

Gitahi, S. M., Piero, M. N., Mburu, D. N., & Machocho, A. K. (2021). Repellent effects of selected organic leaf extracts of *Tithonia diversifolia* (Hemsl.) A. Gray and *Vernonia lasiopus* (O. Hoffman) against *Sitophilus zeamais* Motschulsky (Coleoptera: Curculionidae). *The Scientific World Journal*, 1–13. https://doi.org/10.1155/2021/2718629

Habeeb, H. J., Luaibi, H. M., Dakhil, R. M., Kadhum, A. a. H., Al-Amiery, A. A., & Gaaz, T. S. (2018). Development of new corrosion inhibitor tested on mild steel supported by electrochemical study. *Results in Physics*, *8*, 1260–1267. https://doi.org/10.1016/j.rinp.2018.02.015

Hikmawanti, N. P. E., Fatmawati, S., & Asri, A. W. (2021). The effect of ethanol concentrations as the extraction solvent on antioxidant activity of Katuk (*Sauropus androgynu*s (L.) Merr.) Leaves Extracts. *IOP Conference Series. Earth and Environmental Science*, *755*(1), 012060. https://doi.org/10.1088/1755-1315/755/1/012060

Hoyos-Arbeláez, J., Blandón-Naranjo, L., Vázquez, M., & Contreras-Calderón, J. (2018). Antioxidant capacity of mango fruit (*Mangifera indica*). An electrochemical study as an approach to the spectrophotometric methods. *Food Chemistry*, *266*, 435–440. https://doi.org/10.1016/j.foodchem.2018.06.044

Jahurul, M., Zaidul, I., Ghafoor, K., Al-Juhaimi, F. Y., Nyam, K., Norulaini, N., Sahena, F., & Omar, A. M. (2015). Mango (*Mangifera indica* L.) by-products and their valuable components: A review. *Food Chemistry*, *183*, 173–180. https://doi.org/10.1016/j.foodchem.2015.03.046

Kalisa, N. D., Muhizi, T., Niyotwizera, J. J. Y., Barutwanayo, J. B., & Nkuranga, J. B. (2020). Kinetics and thermodynamics investigations on corrosion inhibiting properties of coffee husks extract on mild steel in acidic medium. *Rwanda Journal of*

Engineering, Science, Technology and Environment, *3*(1). https://doi.org/10.4314/rjeste.v3i1.10

Khasani, N., Kusmono, N., Utami, P., & Budiarto, R. (2021). Corrosion in geothermal facilities: Their causes, effects, mitigation, and worldwide cases. *AIP Conference Proceedings*. https://doi.org/10.1063/5.0066755

Khodair, Z. T., Khadom, A. A., & Jasim, H. A. (2019). Corrosion protection of mild steel in different aqueous media via epoxy/nanomaterial coating: preparation, characterization and mathematical views. *Journal of Materials Research and Technology/Journal of Materials Research and Technology*, *8*(1), 424–435. https://doi.org/10.1016/j.jmrt.2018.03.003

Kumar, H., Yadav, V., Anu, N., Saha, S. K., & Kang, N. (2021). Adsorption and inhibition mechanism of efficient and environment friendly corrosion inhibitor for mild steel: Experimental and theoretical study. *Journal of Molecular Liquids*, *338*, 116634. https://doi.org/10.1016/j.molliq.2021.116634

Kumar, M., Saurabh, V., Tomar, M., Hasan, M., Changan, S., Sasi, M., Maheshwari, C., Prajapati, U., Singh, S., Prajapat, R. K., Dhumal, S., Punia, S., Amarowicz, R., & Mekhemar, M. (2021). Mango (Mangifera indica L.) leaves: Nutritional composition, phytochemical profile, and health-promoting bioactivities. *Antioxidants*, *10*(2), 299. https://doi.org/10.3390/antiox10020299

Maldonado-Celis, M. E., Yahia, E. M., Bedoya, R., Landázuri, P., Loango, N., Aguillón, J., Restrepo, B., & Ospina, J. C. G. (2019). Chemical composition of mango (Mangifera indica L.) fruit: Nutritional and phytochemical compounds. *Frontiers in Plant Science*, *10*. https://doi.org/10.3389/fpls.2019.01073

Philippine Statistics Authority. (2023) *Major Fruit Crops Quarterly Bulletin, April-June 2023*. https://psa.gov.ph/major-fruit-crops/mango

Mazumder, M. a. J. (2020). Global impact of corrosion: Occurrence, cost and mitigation. *Global Journal of Engineering Sciences*, *5*(4). https://doi.org/10.33552/gjes.2020.05.000618

Muthukrishnan, P., Jeyaprabha, B., & Prakash, P. (2017). Adsorption and corrosion inhibiting behavior of Lannea coromandelica leaf extract on mild steel corrosion. *Arabian Journal of Chemistry*, *10*, S2343–S2354. https://doi.org/10.1016/j.arabjc.2013.08.011

Najafi, K., Harpster, T., Kim, H., Mitchell, J., Welch, W., & Karazi, S. (2016). Wafer Bonding. *Elsevier eBooks*. https://doi.org/10.1016/b978-0-12-803581-8.00527-0

Nesic, S., Sun, W., & Bhuiyan, M. (2017). Corrosion in acid gas solutions. *Elsevier eBooks*. https://doi.org/10.1016/b978-0-12-803581-8.10476-x

Omran, M. A., Fawzy, M., Mahmoud, A. E. D., & Abdullatef, O. A. (2022). Optimization of mild steel corrosion inhibition by water hyacinth and common reed extracts in acid media using factorial experimental design. *Green Chemistry Letters and Reviews*, *15*(1), 216–232. https://doi.org/10.1080/17518253.2022.2032844

Oyekunle, D., Agboola, O., & Ayeni, A. (2019). Corrosion inhibitors as building evidence for Mild steel: a review. *Journal of Physics. Conference Series*, *1378*(3), 032046. https://doi.org/10.1088/1742-6596/1378/3/032046

Parvez, G. M., & Akanda, K. M. (2019). Foods and arthritis: An overview. *Elsevier eBooks* (pp. 3–22). https://doi.org/10.1016/b978-0-12-813820-5.00001-5

Quraishi, M. A., Chauhan, D.D., & Saji, V.S. (2021). Heterocyclic biomolecules as green corrosion inhibitors. *Journal of Molecular Liquids*, 341. https://doi.org/10.1016/j.molliq.2021.117265

Ramezanzadeh, M., Bahlakeh, G., & Ramezanzadeh, B. (2019). Study of the synergistic effect of Mangifera indica leaves extract and zinc ions on the mild steel corrosion inhibition in simulated seawater: Computational and electrochemical studies. *Journal of Molecular Liquids*, *292*, 111387. https://doi.org/10.1016/j.molliq.2019.111387

Ramezanzadeh, M., Bahlakeh, G., Sanaei, Z., & Ramezanzadeh, B. (2019). Corrosion inhibition of mild steel in 1 M HCl solution by ethanolic extract of eco-friendly Mangifera indica (mango) leaves: Electrochemical, molecular dynamics, Monte Carlo and ab initio study. *Applied Surface Science*, *463*, 1058–1077. https://doi.org/10.1016/j.apsusc.2018.09.029

Rao, U. M., Dudekula, J. B., Bhatt, S., Kumar, M. S., Shah, K., Chauhan, N. S., & Shilpi, S. (2023). Role of phytopharmaceuticals in inflammatory disorders. *Elsevier eBooks* (pp. 433–451). https://doi.org/10.1016/b978-0-323-99125-4.00002-0

Rashid, M. M., Cho, K. H., & Chung, G. (2013). Rapid thermal annealing effects on the microstructure and the thermoelectric properties of electrodeposited Bi2Te3 film. *Applied Surface Science*, *279*, 23–30. https://doi.org/10.1016/j.apsusc.2013.03.112

Sabzi, R., & Arefinia, R. (2019). Investigation of zinc as a scale and corrosion inhibitor of carbon steel in artificial seawater. *Corrosion Science*, *153*, 292–300. https://doi.org/10.1016/j.corsci.2019.03.045

Saha, A. (2016). Boiler tube failures. *Elsevier eBooks* (pp. 49–68). https://doi.org/10.1016/b978-0-08-100116-5.00003-x

Sanni, O., Fayomi, O. S. I., & Popoola, A. P. I. (2019). Eco-friendly inhibitors for corrosion protection of stainless steel: An overview. *Journal of Physics. Conference Series*, *1378*(4), 042047. https://doi.org/10.1088/1742-6596/1378/4/042047

Sekhar, V., Umakrishna, K., Rao, V. S., & Satyavani, C. (2019). Completely Randomised Design (CRD) analysis – by manual and MS-Excel. *International Journal of Current Microbiology and Applied Sciences*, *8*(03), 954–959. https://doi.org/10.20546/ijcmas.2019.803.114

Shanmugam, H., Nataraj, S., Govindaraj, O., & Thangavel, T. (2023). Plant-based and microbes-mediated synthesis of nanobioconjugates and their applications. In *Comprehensive analytical chemistry, 102,* 123–162. https://doi.org/10.1016/bs.coac.2023.02.003

Singh, D. K., Kumar, S., Udayabhanu, G., & John, R. P. (2016). 4(N,N-dimethylamino) benzaldehyde nicotinic hydrazone as corrosion inhibitor for mild steel in 1 M HCl solution: An experimental and theoretical study. *Journal of Molecular Liquids*, *216*, 738–746. https://doi.org/10.1016/j.molliq.2016.02.012

Srivastava, A., Shekhar, S., Rai, P., & Ayub, A. (2016). Analysis of welding joints and processes. *International Journal of Computer Applications*, 20-26.

Sun, Y., Li, H., Yang, J., & Zhang, J. (2023). Effects of temperature and pressure on corrosion behavior of HVOF-Sprayed FE-Based amorphous coating on the MG-RE alloy for dissolvable plugging tools. *Materials*, *16*(3), 1313. https://doi.org/10.3390/ma16031313

Thakur, A., Assad, H., Kaya, S., & Kumar, A. (2022). Plant extracts as environmentally sustainable corrosion inhibitors II. *Eco-Friendly Corrosion Inhibitors*, 283–310. https://doi.org/10.1016/b978-0-323-91176-4.00017-9

Umoren, S. A., Solomon, M. M., & Saji, V. S. (2022). Pectin and derivatives. In *Polymeric Materials in Corrosion Inhibition* (pp. 255–269). https://doi.org/10.1016/b978-0-12-823854-7.00012-6

Veedu, K. K., Kalarikkal, T. P., Jayakumar, N., & Gopalan, N. K. (2019). Anticorrosive Performance of Mangifera indica L. Leaf Extract-Based Hybrid Coating on Steel. *ACS Omega*, *4*(6), 10176–10184. https://doi.org/10.1021/acsomega.9b00632

Yu, Y., Shironita, S., Souma, K., & Umeda, M. (2018). Effect of chromium content on the corrosion resistance of ferritic stainless steels in sulfuric acid solution. *Heliyon*, *4*(11), e00958. https://doi.org/10.1016/j.heliyon.2018.e00958

Zarras, P., & Stenger-Smith, J. D. (2015). Smart inorganic and organic pretreatment coatings for the inhibition of corrosion on Metals/Alloys. In *Intelligent Coatings for Corrosion Control* (pp. 59–91). https://doi.org/10.1016/b978-0-12-411467-8.00003-9