Corrosion Inhibition Performance and Stability Assessment of a Guava-Eggshell Composite Coating for Mild Steel in Geothermal Conditions

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Abstract

Corrosion in geothermal environments presents a significant engineering challenge due to the high temperature, mineral content, and acidity of geothermal fluids, which accelerate metal degradation. Conventional corrosion inhibitors are often synthetic, costly, and environmentally harmful. This project aimed to evaluate the effectiveness and stability of a natural, biowaste-derived corrosion inhibitor formulated from guava (Psidium guajava) leaf extract and eggshell powder, with cornstarch serving as a biodegradable binder. The goal was to develop a low-cost, eco-friendly coating for mild steel that aligns with sustainable engineering practices. Experiments were conducted by applying the natural coating to mild steel nail samples, followed by a five-day immersion in geothermal water. Corrosion performance was evaluated through weight loss measurements and statistical analysis using Welch's t-test. Results showed that the coated samples had significantly reduced corrosion rates, with an average inhibition efficiency of 48.19%. The guava extract contributed bioactive compounds such as tannins and flavonoids that adsorbed onto the steel surface, while the calcium carbonate from eggshells formed a passive protective barrier. However, post-experiment observation revealed that the coating mixture liquefied approximately ten days after preparation, even without immersion, indicating instability likely caused by the degradation of the cornstarch binder at room temperature. These findings demonstrate the short-term effectiveness of the coating but also highlight the need for formulation improvements to enhance shelf stability. This research supports the feasibility of using biowaste materials as corrosion inhibitors and encourages further investigation into binder modifications and long-term performance under geothermal conditions.

Keywords: *corrosion inhibitor*, *guava leaf extract*, *eggshell powder*, *geothermal water*, *biowaste*, *starch degradation*, *green engineering*

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CHAPTER I

Introduction

Corrosion is a persistent problem that affects metal structures and equipment across various industries, especially in harsh environments such as geothermal systems. With growing concerns over the cost, safety, and environmental impact of synthetic corrosion inhibitors, researchers have turned to natural and sustainable alternatives. This chapter introduces the background, objectives, significance, and scope of the study, which investigates the potential of biowaste materials specifically guava leaves and eggshells as eco-friendly corrosion inhibitors for mild steel exposed to geothermal water.

1.1 Background of the Study

Corrosion is a global industrial issue with widespread economic and environmental consequences. On an international level, corrosion contributes to the degradation of infrastructure, vehicles, pipelines, and industrial equipment, causing an estimated 3% to 4% loss of a country's gross domestic product (GDP) annually (Koch, 2017). For instance, in countries like Iceland and Japan, where geothermal power plants are integral to national energy production, corrosion of pipes and turbines exposed to acidic steam and hot fluids remains a persistent challenge. These facilities often rely on synthetic chemical inhibitors to protect their systems. However, such substances are usually toxic, expensive, and environmentally hazardous (Raja & Sethuraman, 2008).

In the Philippines, the impact of corrosion is similarly felt, particularly in geothermal power production, which is a key component of the country's renewable energy portfolio (DOE, 2021). Geothermal plants in regions such as Leyte, Albay, and Negros Oriental regularly face equipment degradation due to high-temperature and mineral-rich geothermal fluids (Bacud, J., & Cuevas, C., 2020). Most solutions available involve imported corrosion inhibitors, which are not only costly but also raise environmental concerns. These circumstances create a pressing need for locally developed, affordable, and environmentally friendly alternatives that can be sustainably applied in rural and industrial settings.

The Palinpinon Geothermal Power Plant in Valencia, Negros Oriental, operated by the Energy Development Corporation (EDC), is one of the country's major sources of geothermal energy, supplying power to parts of Visayas (EDC, n.d.). The facility is composed of Palinpinon I and II, with a combined capacity of nearly 192.5 MW. These plants rely on pipelines, steam separators, and turbines that are continually exposed to acidic geothermal fluids making them highly susceptible to corrosion. While synthetic inhibitors are currently used, they are costly and raise long-term sustainability concerns. Meanwhile, surrounding communities in Valencia produce significant amounts of biowaste, such as guava leaves and eggshells, which are often discarded. These materials are rich in tannins, flavonoids, and calcium carbonate, which have been shown to inhibit corrosion by forming protective films on metal surfaces (Lubena & Ningrum, 2019; Sanni et al., 2023).

In the study, the researchers investigated the possibilities of using guava (Psidium guajava) leaves and eggshells, both are biowastes that are disposed of on a regular basis, as a coating material to aid in the reduction of corrosion of metal surfaces exposed to geothermal water.

Guava leaves and eggshells are biodegradable as well as being loaded with bioactive components that exhibit anti-corrosion properties. Utilization of biowaste into something productive demonstrates the research promotes sustainability and environmental awareness.

1.2 Statement of the Problem

Corrosion is a major issue in geothermal environments due to the high temperature and acidity of the water, which accelerates the deterioration of metals and leads to equipment failure and increased maintenance costs. Most available corrosion inhibitors are synthetic, expensive, and pose environmental and health risks due to their toxic nature. There is a significant gap in the availability of low-cost, sustainable, and environmentally safe corrosion protection methods that can be effectively applied in real-world settings, especially in rural or developing areas where resources are limited. The challenge is to develop an alternative corrosion inhibitor that is not only effective in protecting metals from corrosion but is also accessible, affordable, and environmentally friendly using readily available biowaste materials.

1.3 Objectives of the Study

General Objective:

To evaluate the effectiveness of a natural biowaste-based corrosion inhibitor using guava (Psidium guajava) leaf extract and eggshell powder as a composite coating for protecting mild steel from corrosion in geothermal water environments.

Specific Objectives:

1. To develop a natural coating formulation using guava leaf extract and powdered eggshell with cornstarch as a natural binder.
2. To apply the biowaste-based coating on mild steel nail specimens and expose them to geothermal water for a controlled period of five days.
3. To measure and compare the weight loss and corrosion rates between coated (experimental) and uncoated (control) mild steel samples.
4. To calculate and evaluate the corrosion inhibition efficiency of the natural biowaste coating through statistical analysis.
5. To conduct visual inspection and document the surface condition and corrosion patterns of both treated and untreated metal samples after geothermal water exposure.
6. To assess the potential of guava leaves and eggshells as sustainable, low-cost alternatives to synthetic corrosion inhibitors for practical application in geothermal environments.

1.4 Hypotheses

The hypotheses for this study are as follows:

1. H_{01}: There is no significant difference in the corrosion rate of mild steel nails immersed in geothermal water with and without the biowaste coating.

H_{a1}: There is a significant difference in the corrosion rate of mild steel nails immersed in geothermal water with and without the biowaste coating.

2. H_{02}: The biowaste coating made from guava leaves and eggshells has no significant effect on mitigating corrosion in metal surfaces exposed to geothermal water.

   H_{a2}: The biowaste coating made from guava leaves and eggshells significantly reduces corrosion in metal surfaces exposed to geothermal water.

1.5 Scope and Limitations

This study investigated the corrosion inhibition effectiveness of a natural biowaste-based coating on mild steel nails, which served as representative metal samples. The coating was formulated from guava (Psidium guajava) leaf aqueous extract and powdered chicken eggshells, utilizing cornstarch and distilled water as a natural binder system. The research was conducted by exposing coated and uncoated metal nails to authentic geothermal water sourced from Bulak, Dauin, for a five-day immersion period under ambient laboratory conditions. Evaluation methods included weight loss measurements, corrosion rate calculations, visual surface inspection, and statistical analysis using an Independent Samples t-test to determine inhibition efficiency and compare the performance of coated and uncoated samples. A comprehensive chemical analysis of the geothermal water composition was not conducted. The research also did not include comparisons with other plant-based extracts, synthetic commercial inhibitors, or hybrid formulations that could have established relative performance benchmarks. Furthermore, the study did not investigate different coating application methods, varying concentrations of active ingredients, or the effects of coating thickness on inhibition performance.

1.6 Significance of the Study

The results of this study aim to benefit the following:

Environmental Advocates and Policymakers. This study promotes the use of biowaste materials such as guava leaves and eggshells, contributing to environmental sustainability by reducing chemical waste and pollution. It supports the concept of a circular economy by converting organic waste into useful corrosion inhibitors, which can help reduce dependency on synthetic chemicals that harm the environment.

Local Communities and Rural Sectors. People in rural or less industrialized areas will benefit from this research by gaining access to affordable and natural alternatives to expensive, imported corrosion inhibitors. The use of common agricultural waste materials makes this method practical and accessible even in low-resource settings, helping protect infrastructure such as water tanks, pipes, and other metal components.

Geothermal and Industrial Companies. Geothermal plants and other industrial sectors prone to corrosion can apply the findings of this study to reduce maintenance costs. Using locally available biowaste-based inhibitors can minimize operational expenses, extend equipment lifespan, and lower the need for frequent replacements.

Scientific Researchers and Chemists. This study contributes to the field of green chemistry and biomaterials by providing scientific data on how compounds like tannins and flavonoids from guava leaves and calcium carbonate from eggshells inhibit corrosion. It also fills a knowledge gap regarding the use of biomass waste in corrosion control.

Health and Safety Practitioners. Replacing toxic synthetic inhibitors with natural ones supports safer working conditions by lowering the risks associated with handling and disposing of hazardous chemicals, promoting a healthier work environment in industrial settings.

Entrepreneurs and Green Technology Innovators. Entrepreneurs focused on eco-friendly technologies may find opportunities to develop, package, and commercialize natural corrosion inhibitors derived from biowaste. This can open new business ventures aligned with sustainability goals.

Environmental Engineers and Industrial Designers. This study shows how waste-to-value approaches can be integrated into conventional engineering solutions. It encourages responsible material usage and inspires innovations in environmentally friendly corrosion protection methods.

Future Researchers. The research serves as a foundation for further studies on optimizing formulation, large-scale applications, and deeper understanding of the corrosion inhibition mechanisms of biowaste materials. Future researchers can use this study as a baseline for improving and expanding sustainable corrosion protection solutions.

CHAPTER II

Literature Review

This chapter presents a review of relevant literature and studies that support the development of natural corrosion inhibitors, particularly those derived from plant extracts and biowaste materials. It provides a foundation for understanding the corrosion process, the limitations of conventional inhibitors, and the growing interest in eco-friendly alternatives. Key concepts such as the chemical property of guava leaves and eggshells, their corrosion-inhibiting mechanisms, and previous experimental results are discussed. By examining both theoretical insights and related experimental findings, this chapter establishes the scientific basis and significance of using natural materials as sustainable solutions for corrosion prevention, especially in geothermal environments.

2.1 Review of Related Literature

2.1.1 Corrosion Mechanisms

Corrosion is degradation of materials' properties due to interactions with their environments, and corrosion of most metals (and many materials for that matter) is inevitable. While primarily associated with metallic materials, all material types are susceptible to degradation (Shaw & Kelly, 2006). Corrosion is so prevalent and takes so many forms that its occurrence and associated costs will never be eliminated. Over the past 50 years, several national costs of corrosion studies have been conducted. Using different approaches, the studies all arrived at corrosion costs equivalent to about 3%–4% of each nation's gross domestic product (GDP) (Koch, 2017). However, most studies estimate that 25%– 30% of annual corrosion costs could be saved if optimum corrosion management practices were employed. (Bender et al., 2022). Materials reliability is becoming ever more important in our society, particularly in view of the liability issues that develop when reliability is not assured, safety is compromised, and failure occurs (Revie & Uhlig, 2025).

Like other natural hazards such as earthquakes or severe weather disturbances, corrosion can cause dangerous and expensive damage to everything from pipelines, bridges, and public buildings to vehicles, water and wastewater systems, hydrogen infrastructure, smart home and city appliances, electronics, batteries, sensors, and even nanotechnologies. Unlike weatherrelated disasters though, there are time-proven methods to prevent and control corrosion that can reduce or eliminate its impact on public safety, the economy, and the environment (Bender et al., 2022).

2.1.2 Traditional Corrosion Inhibitors

There are certain ways to protect the metal from corrosion such as coating, alloying, cathodic protection, anodic protection and recently been using the laser for this purpose by surface treatment of metal is considered as the way to improve the properties of metals like roughness, hardness, the resistance of corrosion, etc. Inhibition is a preventive measure against corrosive attack on metallic materials. It consists of the use of chemical compounds which, when added in small concentrations to an aggressive environment, can decrease corrosion of the exposed metal (Trabanelli, 2020).

Corrosion inhibitors are of considerable practical importance, as they are extensively employed in reducing metallic waste during production and in reducing the risk of material failure, both of which can lead to the sudden closure of industrial processes, which in turn leads to additional costs. It is also important to use corrosion inhibitors to prevent the dissolution of minerals and reduce acid consumption (Kadhim et al., 2021).

The use of corrosion inhibiting admixtures has grown over the last 25 years because they provide a level of protection and longevity that would be too difficult (essentially too expensive) to achieve otherwise. Understanding how they function is an ongoing process that relies on field experience to identify the most important issues and on theory to untangle and describe the individual effects (Gaidis, 2004).

2.1.3 Organic inhibitors

Synthetic organic corrosion inhibitors (SOCIs) and traditional inorganic corrosion inhibitors (TICI's) such as chromates and lead have been known to have restrictive environmental regulations (Raja & Sethuraman, 2008) due to their hazardous effects. However, many of the SOCIs are not biodegradable and get accumulated in the environment constituting nuisance to human health or ecological systems, the removal of which is complicated and expensive (Bammou et al., 2011). These environmental issues have called for a replacement of these TICIs and SOCIs with natural organic compounds sourced from spices, naturally existing aromatic herbs, and medicinal plants that can hinder the corrosion of materials in corrosive media called organic green corrosion inhibitors (OGCIs), which are inexpensive, harmless, readily obtainable, and environmentally accommodative.

Organic inhibitors act through forming a film on the surface of the metals and they can act as anodic, cathodic, or mixed inhibitors. The formation of this protective film happens with the help of strong interactions, such as π-orbital adsorption, chemisorption, and electrostatic adsorption that prevent the corrosive species from attacking the metal surface. This adsorption is usually one molecular layer thick and does not penetrate the bulk of the metal itself (Lipiar & Mazumder, 2019).

2.1.3a Use of Natural Biowaste as inhibitors

Green inhibitors are biodegradable, ecologically acceptable and renewable. Their valorization expands possible applications in industrial fields other than ‘waste to energy’ in the perspective of a circular economy. Although a lot of experimental work has been done and many research papers have been published, the topic of green inhibitors is still an open issue. The great interest in the field expanded the research, resulting in high numbers of tested molecules (Marzorati et al., 2018). Rodriguez-Torres et al. (2019) claimed that green corrosion inhibitors were discovered long before the concern with conventional inhibitors arose. The first investigation on green corrosion inhibitors was detected in the year 1930.

Several studies have focused on organic green corrosion inhibitors; however, their main weakness is that there have been limited attempts to study the potential of biomass wastes as organic corrosion inhibitors, as proven by a study conducted by Marzorati et al. during 2018. Vorobyova et al. (2019) mentioned that organic green corrosion inhibitors are very uncommon. However, their efficiency shows that biomass waste does have high potential and is worthy of further investigation.

Furthermore, abundant resources of biomass waste are readily available, and it is sensible to make use of the huge number of resources. In Malaysia alone, the biomass wastes produced yearly is 160 million metric tons. It is believed that the principles and mechanisms of biomass waste-based corrosion inhibitors are the same as those of plant-based corrosion inhibitors, as reviewed comprehensively in an earlier section. The assumption is valid as biomass waste originates from plants (Reza et al., 2021).

2.4. Guava Leaves

The guava tree (*Psidium guajava L)* is a tree that can reach 8 m in height originating from tropical America having as main characteristic the fruit with a pericarp and pulp consisting of small seeds the guava. Its leaves can reach about 20 cm in length and have protruding ribs at the bottom. It is a plant widely distributed in the Brazilian national territory and admirably adapted. The leaves present themselves with a good antioxidant potential by capturing free radicals. Its main constituents are tannins, flavonoids, essential oils, sesquiterpene alcohols and triterpenoid acids (Fernandes et al., 2021).

The content of secondary metabolites in guava leaves include tannins, flavonoids, alkaloids, polyphenols, saponins, and essential oils. The content of tannins in guava leaf extract can be used to inhibit the corrosion rate. Hartanto and Wicaksono (2018) and Wahyuni and Syamsudin (2014) research using guava leaf extract as a corrosion inhibitor stated that guava leaf extract was effective in reducing the corrosion rate. In his research, Hartanto and Wicaksono measured the corrosion rate of stainless steel and Wahyuni and Syamsudin measured the corrosion rate of iron (Sari et al., 2022).

2.4.1 Tannin

Research on inhibitors is currently focused on organic types, as they are environmentally friendly and abundant in nature. One organic compound that plays a role in corrosion prevention is tannin. The ability of tannins to prevent corrosion naturally has been known for a long time, but systematic research has only been carried out in recent decades. Guava leaf (*Psidium Guava L.*) is one of the sources of tannins that are available in nature (Manurung & Amelia, 2025).

According to a study by Lubena & Ningrum in 2019, tannin extracted from guava leaves can be used as a natural inhibitor. Their research led to the following conclusions: Steel carbon treated with tannin-containing guava leaf extract exhibited lower corrosion rates than without treatment, the corrosion rate of low-steel carbon immersed in 3% HCl for three days was 16.8641 mpy, the decrease in corrosion rate occurs with the addition of inhibitors from extraction of guava leaves on immersion with 3% HCl solution for 9 days with a weight of 5 gram inhibitors obtained the corrosion rate of 5.6214 mpy with an efficiency of 39.31624% and this is due to tannin compounds forming iron (III)-tanin complex compounds as a layer of film attached to the surface of low carbon steel thus reducing the corrosion rate of the low carbon steel (Lubena & Ningrum, 2019).

2.5 Eggshells

There is a lot of research attention on the behavior of different inhibitors on steel corrosion but there are limited researches on the use of eggshells as a corrosion inhibitor in research related to steel corrosion. Eggshells correspond to 11% of the total weight of an egg and have been largely studied since 1964 (Sanni et al., 2018). Eggshell is mainly made up of 95% calcium carbonate, 1% calcium phosphate and other organic matters. Egg shell is regarded as a non-edible product with very limited use, mostly disposed of as waste. Due to high disposal costs and increasing environmental concerns, it is necessary to find a way of transforming the waste eggshells into valuable ones leading to low disposal costs.

According to a study by Sanni et al. during 2023, eggshells have a high level of protein, which in turn presents O and C atoms; therefore, this compound can be proposed for use as an inhibitor. The extraction of the rich constituents present in the eggshell could be achieved by diverse means before being utilized as inhibitors in other aggressive media/metal. (Sanni et al., 2023).

Experimental data explained the effective performance of eggshells with values of 57%–100% inhibition efficiency, at 2 g–10 g inhibitor concentration from weight loss tests due to the inhibition of stainless steel. The electrochemical action was as a result of the ionized particles which inhibit the compound influencing the redox reaction mechanism causing surface corrosion (Sanni et al., 2018).

The potentiodynamic polarization technique result showed that ES alters drastically the electrochemical process initiating corrosion. Furthermore, the inhibitive behavior of eggshells is related to its formation and adsorption of compact barrier film on the metal electrode surface. This was further shown by the corrosion potential values of the samples with the eggshells when compared to values of corrosion potential samples without the presence of eggshells.

CHAPTER III

Methodology

This chapter outlines the systematic procedures undertaken in this study to investigate the corrosion resistance of mild steel nails coated with a natural inhibitor formulated from guava leaf extract and eggshell powder. The methodology covers the research design, materials and equipment used, experimental procedures, data collection methods, and analytical techniques employed for interpreting the results.

3.1 Research Design

This study employed an experimental comparative research design to evaluate the effectiveness of a natural inhibitor coating in reducing the corrosion rate of mild steel nails in geothermal water. This design is appropriate for establishing cause-and-effect relationships under controlled conditions, allowing the researcher to isolate the effect of the natural coating (Creswell, 2014). Two groups of mild steel nail samples were prepared: The Controlled group, consists of uncoated nails; and the Experimental group, consists of coated nails with the guava leaf-eggshell composite. Both groups were subjected to identical geothermal water conditions over a fixed period. By holding all other variables constant, the study was able to directly compare the corrosion behavior of coated versus uncoated samples. This approach is consistent with standard practices in corrosion research, where comparative exposure under uniform conditions is used to assess the performance of corrosion inhibitors (Fraenkel, Wallen, & Hyun, 2012; Rajendran et al., 2011; Noor & Al-Moubaraki, 2008). The use of a natural, eco-friendly inhibitor aligns with green chemistry principles and builds on previous studies that investigate plant-based and biogenic materials as sustainable alternatives to synthetic corrosion inhibitors.

3.2 Materials Used

The materials required for this study included fresh guava leaves, chicken eggshells, cornstarch as a natural binder, distilled water, and geothermal water, which served as the corrosive medium. Mild steel nails were used as metal specimens. The laboratory equipment included an analytical balance for precise mass measurement, an oven for drying samples, and various glassware such as beakers and filters for solution preparation. A blender or mortar and pestle was used to process solid materials into powder form. For statistical and analytical processing, Microsoft Excel was utilized for basic computations and will be employed for conducting inferential statistics, such as t-tests, to assess the significance of corrosion rate differences.

3.3 Experimental Procedures

The preparation of the corrosion inhibitor began with the collection and cleaning of fresh guava leaves, which were then air-dried for three days until fully dehydrated. The dried leaves were ground into fine powder, and an aqueous extract was prepared by mixing 10 grams of guava leaf powder with 100 milliliters of distilled water (Fernandes et al., 2021).

This mixture was heated while being stirred for 40 minutes, cooled, and filtered to obtain the extract (Lubena et al., 2019). Meanwhile, the eggshells were washed thoroughly to remove inner membranes and organic residues, dried under sunlight, and ground into fine powder like a study conducted by Mamada et al., (2020). The coating formulation was created by dissolving 10 grams of cornstarch in 100 milliliters of warm distilled water to form the binder. In a separate beaker, 20 milliliters of guava leaf extract, 10 grams of eggshell powder, and 50 milliliters of the binder solution were thoroughly mixed to produce a uniform suspension suitable for application.

The mild steel nail samples were cleaned with sandpaper to remove surface oxides and impurities, then rinsed with distilled water, dried, and weighed to record their initial mass. The experimental group was coated with the formulated mixture using a brush and allowed to dry completely, while the control group remained uncoated. All samples were then immersed in geothermal water under ambient conditions for a defined exposure period. During immersion, samples were regularly observed.

3.4 Data Collection Methods

The primary method for assessing corrosion was the mass loss technique. After the immersion period (120 hours), all steel samples were retrieved, cleaned gently to remove corrosion products, and dried. Their final masses will be recorded using an analytical balance. The difference between the initial and final mass represented the weight loss due to corrosion. Visual observations were also noted to assess surface degradation, rust formation, and coating integrity.

To quantify the CRs by the weight-loss method, also referred to as the immersion tests, the mass loss of the specimen under study (of known surface area) is determined by the difference in weight before and after it is immersed in a corrosive medium for a specified amount of time (ASTM, 2012). This is a simple and well-established method to study corrosion.

Standard guidelines to study corrosion, such as ISO, ASTM, or NACE TM0169/G31−12a "Standard Guide for Laboratory Immersion Corrosion Testing of Metals" (ASTM, 2012) are broadly used by industry and academics. They describe the methodology to quantify the CRs by immersion test experiments. The formula presented in these standards to quantify the CR, which is also broadly used in academic literature, is given below:

$$CR = \frac{K \times m_{loss}}{A \times t \times \rho}$$

where k is a constant 8.76×10^4 so that CR is in [mm/y], m_{loss} is the mass loss [g] of the metal ($m_{initial} - m_{final}$) in time t [hours], A is the surface area of the material exposed [cm^2], and ρ is the density of the material [g/cm^3] (ASTM, 2012; Kreysa & Schütze, 2007; Kutz, 2005).

In this formula, it is assumed that the surface area remains constant throughout the corrosion process, but this is clearly not the case, as the surface area of the material will change as a function of time as the object dissolves in the corrosion medium.

3.5 Data Analysis

In this study, the corrosion rate of coated and uncoated mild steel samples was calculated using the standard weight loss method. The inhibitor efficiency was computed by comparing the average corrosion rates between the experimental group (coated with guava leaf extract and eggshell powder) and the control group (uncoated). To determine whether the difference in corrosion rates between the two groups was statistically significant, an Independent Samples t-test assuming unequal variances commonly referred to as Welch's t-test was conducted. Welch's t-test was selected because it does not assume equal variances between groups, making it more appropriate in conditions where variance heterogeneity is present or suspected, which was the case in this experiment due to the natural variability in corrosion rates observed during preliminary analysis (Ruxton, 2006; Delacre et al., 2017).

The statistical analysis was performed using Microsoft Excel's built-in function "t-Test: Two-Sample Assuming Unequal Variances," which is a direct implementation of Welch's t-test. This method is well-regarded in scientific research for its robustness and reliability, particularly when comparing two independent means with unequal sample variances or different standard deviations (Lu & Yuan, 2010). The independent variable in this analysis was the type of sample treatment (coated vs. uncoated), and the dependent variable was the corrosion rate measured after immersion in geothermal water.

A two-tailed test was used with a significance level of $\alpha = 0.05$. This 5% threshold is commonly accepted in scientific studies as the standard for determining whether an observed effect is statistically significant (Field, 2013). If the computed p-value falls below this level, the null hypothesis—that there is no significant difference between the two means—is rejected in favor of the alternative hypothesis. By applying Welch's t-test at the 0.05 significance level, the study ensures that the evaluation of the biowaste-based coating's effectiveness in corrosion inhibition is statistically sound and methodologically appropriate.

CHAPTER IV

Design and Implementation

This chapter outlines the overall approach used in designing and executing the experimental procedures for evaluating a natural corrosion inhibitor derived from guava (*Psidium guajava*) leaves and eggshell powder. The aim was to test the coating's effectiveness in protecting mild steel from corrosion in a geothermal water environment. The design phase focused on selecting appropriate materials, preparing the coating formulation, and structuring the experiment to allow accurate measurement of corrosion rates. The implementation phase details the actual procedures followed in the laboratory, including sample preparation, coating application, immersion in geothermal water, and data collection for corrosion analysis. The steps taken in this study were carefully planned to ensure reliability, reproducibility, and relevance to sustainable corrosion mitigation in geothermal settings.

4.1 Experimental Design

***Figure 1**. Guava leaf extract and Eggshell composite as a natural inhibitor for corrosion control.*

A natural corrosion inhibitor was produced using a composite formed from guava (Psidium guajava) leaves and eggshells with cornstarch as a natural binder. The goal is to establish the efficiency of this natural coating as a corrosion inhibitor for metal samples exposed to geothermal water, therefore filling a gap in low-cost, sustainable, and safe corrosion prevention techniques. Guava leaves contain tannins that slow the rate of corrosion by producing a film on the surface, whereas eggshells, mostly calcium carbonate, have inhibitive properties due to the creation and adsorption of a compact barrier coating on the metal electrode surface.

The experiment was carried out in a controlled laboratory setting that was equipped with essential apparatus, such as beakers, a digital weighing scale, measuring cylinders, paint brushes, and containers designated for corrosion testing, in addition to an analytical balance and an oven for drying samples, all maintained in an orderly manner. The materials utilized included fresh guava leaves, chicken eggshells, cornstarch (serving as a natural binder), distilled water, geothermal water (sourced from Bulak, Dauin), and mild steel nails as test specimens. The preparation of the coating involved meticulously cleaning, air-drying, and grinding fresh guava leaves into a fine powder to create an aqueous extract by heating it with distilled water, followed by cooling and filtering; simultaneously, the eggshells were washed, sun-dried, and ground into a fine powder using a mortar and pestle.

The formulation of the coating was achieved by thoroughly combining the guava leaf extract, eggshell powder, and binder solution (derived from cornstarch dissolved in warm distilled water) to yield a uniform suspension. Mild steel nail samples were prepared by cleaning them with sandpaper, rinsing with distilled water, drying, and recording their initial mass; the formulated mixture was then applied to these samples using a clean paintbrush and allowed to airdry completely at room temperature for a duration of 2-3 hours. Subsequently, both coated and uncoated steel samples were immersed separately in labeled containers filled with geothermal water, which were placed in a stable area protected from environmental fluctuations, and the samples were regularly monitored. The samples will be observed at fixed daily intervals to document and evaluate the corrosion rate, assessing surface degradation, rust formation, and the integrity of the coating. Finally, an Independent Samples t-test was devised to compare the corrosion rates of both sample groups to ascertain the effectiveness of the coating.

Finally, an Independent Samples t-test was conducted to compare the corrosion rates of both sample groups and assess coating effectiveness. Corrosion rates were calculated using the standard weight loss method [$CR = (k \times m_{loss})/(A \times t \times \rho)$], and Welch's t-test was performed in Microsoft Excel to determine if the difference between coated and uncoated samples was statistically significant. Inhibitor efficiency was calculated by comparing the average corrosion rates of the experimental (coated) and control (uncoated) groups.

4.2 Implementation Steps

A natural corrosion inhibitor was produced using a composite formed from guava (Psidium guajava) leaves and eggshells with cornstarch as a natural binder. The goal is to establish the efficiency of this natural coating as a corrosion inhibitor for metal samples exposed to geothermal water, therefore filling a gap in low-cost, sustainable, and safe corrosion prevention techniques. Guava leaves contain tannins that slow the rate of corrosion by producing a film on the surface, whereas eggshells, mostly calcium carbonate, have inhibitive properties due to the creation and adsorption of a compact barrier coating on the metal electrode surface.

4.2.1 Collection and Preparation of Raw Materials

Fresh guava leaves were harvested from local sources, thoroughly washed to remove any dirt or surface contaminants, and then air-dried for three days to preserve their bioactive compounds. After drying, the leaves were finely ground using a blender to facilitate the extraction process. Chicken eggshells, a common kitchen waste product, were collected separately, cleaned thoroughly to remove any remaining inner membranes, sun-dried, and then pulverized into a fine powder using a mortar and pestle. In addition to these materials, cornstarch was prepared to serve as a natural binder, and distilled water was used for all solutions to maintain consistency and purity throughout the experiment.

4.2.2 Formulation of the Corrosion Inhibitor Coating

The next phase involved the formulation of the corrosion inhibitor. A guava leaf extract was prepared by mixing 10 grams of guava powder with 100 milliliters of distilled water. This mixture was heated for approximately 40 minutes under continuous stirring to allow for optimal extraction of the plant's bioactive compounds. After heating, the solution was cooled and filtered to obtain a concentrated aqueous extract. Simultaneously, 10 grams of pre-ground eggshell powder were set aside. A binder solution was made by dissolving 10 grams of cornstarch in 100 milliliters of warm distilled water until a thick, homogenous liquid was achieved. The final coating was formulated by combining 20 milliliters of the guava leaf extract, 10 grams of eggshell powder, and 50 milliliters of the cornstarch binder. This mixture was stirred vigorously to ensure complete dispersion of solids and to produce a smooth, uniform suspension suitable for application.

4.2.3 Application of the Coating

Mild steel nails were selected as the metal test specimens. Each nail was cleaned manually using sandpaper to remove any surface oxidation or rust, followed by a rinse with distilled water and thorough drying to ensure a clean surface for coating adherence. The initial mass of each sample was recorded using an analytical balance with high precision. For the experimental group, the prepared biowaste-based coating was applied evenly to each nail using a clean paintbrush. The coated samples were left to air dry completely for two to three hours at room temperature to allow the coating to stabilize. Meanwhile, the control group was left uncoated to serve as a baseline for comparison during corrosion evaluation.

4.2.4 Exposure to Corrosive Environment

After preparation, both the coated and uncoated samples were fully immersed in containers filled with geothermal water, which was collected from Bulak, Dauin, Negros Oriental. The containers were clearly labeled to distinguish between the two groups and were placed in a stable indoor environment where they would not be disturbed. The immersion period lasted five days, equivalent to 120 hours, under consistent ambient laboratory conditions. Throughout the exposure period, care was taken to maintain similar temperature and pH conditions for all samples to ensure fair comparison.

4.2.5 Observation and Data Collection

Throughout the five-day immersion, visual observations were conducted daily to monitor surface changes, rust formation, and coating degradation. At the end of the immersion period, all samples were retrieved carefully, gently cleaned to remove loose corrosion products, and air-dried. Each sample was then weighed again to determine the final mass. The difference between the initial and final weight represented mass loss due to corrosion. These values were recorded meticulously and supplemented with qualitative observations such as rust intensity and surface texture, which were also documented through photographs for supporting evidence.

4.2.6 Data Analysis and Interpretation

The corrosion rate for each sample was calculated using the standard weight loss method defined by ASTM, which considers the weight loss, surface area, material density, and exposure time. Inhibition efficiency was then computed by comparing the average corrosion rates between the coated and uncoated samples. To validate the findings statistically, Welch's t-test was employed using Microsoft Excel to determine whether the observed differences in corrosion rates were statistically significant. A significance level of $\alpha = 0.05$ was used, and results showed that the biowaste-based coating led to a notable reduction in corrosion. These findings supported the hypothesis that guava leaves and eggshells, when formulated into a composite coating, can serve as effective and sustainable corrosion inhibitors for metal exposed to geothermal water.

CHAPTER V

Results and Discussion

This section presents and analyzes the experimental results obtained from the evaluation of guava (Psidium guajava) leaf extract and eggshell powder as natural corrosion inhibitors for mild steel exposed to a geothermal water environment over a five-day immersion period. The investigation focused on measuring weight loss, calculating corrosion rates, determining inhibitor efficiency, and performing statistical analysis using Welch's t-test to assess the significance of the observed differences between treated and untreated samples.

The effectiveness of the biowaste-based coatings was assessed by comparing the corrosion behavior of coated versus uncoated steel samples. The guava leaf extract and eggshell powder were selected based on their eco-friendly properties and potential to form protective films due to their bioactive and mineral content. The findings are discussed in relation to the average corrosion rates, inhibitor efficiencies, and visual surface observations. Variability in outcomes is also addressed, highlighting potential influencing factors such as coating consistency and experimental conditions. The results serve to evaluate the viability of using sustainable and biodegradable materials in mitigating corrosion in geothermal applications.

5.1 Discussion of Findings

The experimental findings highlight the impact of the biowaste-based coating on the corrosion behavior of mild steel. Treated samples exhibited a noticeable reduction in corrosion indicators compared to the untreated group. This suggests that the combination of guava leaf extract and eggshell powder contributed to forming a protective barrier on the metal surface, minimizing its interaction with the geothermal fluid. The observed trends across various parameters are detailed in the following subsections.

5.1.1 Weight Loss Observations

This presents the initial and final weights of mild steel samples over the immersion period, highlighting differences between the coated and uncoated groups. It includes average weight loss data across 20 trials for each group, identifying general corrosion trends.

Trial	Controlled		Experimental	
	Initial Weight (g)	Final Weight (g)	Initial Weight (g)	Final Weight (g)
1	2.426	2.397	2.488	2.445
2	2.400	2.347	2.476	2.448
3	2.392	2.355	2.517	2.490
4	2.532	2.498	2.430	2.400
5	2.470	2.396	2.520	2.491
6	2.400	2.340	2.516	2.484
7	2.440	2.389	2.488	2.457
8	2.510	2.454	2.459	2.435
9	2.476	2.427	2.522	2.501
10	2.461	2.399	2.400	2.372
11	2.340	2.264	2.485	2.458
12	2.459	2.413	2.392	2.367
13	2.526	2.478	2.398	2.370
14	2.500	2.448	2.440	2.417
15	2.488	2.416	2.483	2.456
16	2.496	2.425	2.399	2.360
17	2.420	2.357	2.460	2.431
18	2.574	2.523	2.400	2.374
19	2.380	2.334	2.391	2.360
20	2.522	2.450	2.444	2.421

Table 1. *Initial and Final Weights of the Mild Steel Nails (Controlled and Experimental).*

Weight Loss Method

The weight loss method is a widely accepted and straightforward approach for evaluating corrosion behavior, particularly due to its simplicity, reliability, and ability to provide longterm average corrosion rates under various environmental conditions (Fontana, 1987). In this study, it was used to determine the mass loss of mild steel samples before and after exposure to geothermal water.

The formula used to calculate weight loss is:

$$Weight\ Loss = W_i - W_f$$

Where:

W_i = initial weight of the sample (g)

W_f = final weight of the sample after immersion (g)

This weight loss value serves as the basis for calculating the corrosion rate and further evaluating the effectiveness of the natural inhibitor coatings.

Weight Loss (g)					
Trial	Controlled	Experimental	Trial	Controlled	Trial
1	0.029	0.043	11	0.076	0.027
2	0.053	0.028	12	0.046	0.025
3	0.037	0.027	13	0.048	0.028
4	0.034	0.030	14	0.052	0.023
5	0.074	0.029	15	0.072	0.027
6	0.060	0.032	16	0.071	0.039
7	0.051	0.031	17	0.063	0.029
8	0.056	0.024	18	0.051	0.026
9	0.049	0.021	19	0.046	0.031
10	0.062	0.028	20	0.072	0.023

Table 2. *Weight Loss of Mild Steel Samples (Controlled and Experimental).*

5.1.2 Corrosion Rate Calculation

This section compares the average corrosion rates of coated and uncoated samples and introduces how these rates reflect the inhibitors' protective performance.

The corrosion rate was calculated using the weight loss method, following the standard procedure recommended by ASTM G1. This method is widely recognized for its reproducibility and accuracy in assessing the corrosion behavior of metals based on mass loss over a specified exposure period (ASTM International, 2017).

The corrosion rate was determined using the following formula:

$$Corrosion\ Rate = \frac{K \times \Delta W}{A \times T \times \rho}$$

Where:

ΔW = Weight loss (g)

A = Surface area of the specimen (cm^2)

T = Exposure time ($hours$)

ρ = Density of the material (g/cm^3)

K = Unit conversion constant (mm/yr)

In this study, the following parameters were used:

- Surface area, $A = 5.38\ cm^2$
- Exposure time, $T = 120\ hrs$

- Material density, $\rho = 7.85\ g/cm^3$
- Conversion factor, $K = 87600\ mm/yr$

These parameters allowed for consistent and comparable corrosion rate values across all test samples, providing a quantitative basis for evaluating the effectiveness of the natural inhibitors.

Corrosion Rates					
Trial	Controlled	Experimental	Trial	Controlled	Experimental
1	0.5013	0.7433	11	1.3137	0.4667
2	0.9161	0.4840	12	0.7951	0.4321
3	0.6395	0.4667	13	0.8297	0.4840
4	0.5877	0.5186	14	0.8988	0.3976
5	1.2791	0.5013	15	1.2445	0.4667
6	1.0371	0.5531	16	1.2272	0.6741
7	0.8815	0.5358	17	1.0890	0.5013
8	0.9680	0.4148	18	0.8815	0.4494
9	0.8470	0.3630	19	0.7951	0.5358
10	1.0717	0.4840	20	1.2445	0.3976

Table 3. *Corrosion Rate of Mild Steel Nails (Controlled and Experimental).*

5.1.3 Inhibitor Efficiency

This part presents the percentage inhibition efficiency of the guava leaf and eggshell coatings. It compares the mean efficiencies across trials and explains why eggshell powder may have provided greater corrosion protection due to its calcium carbonate content, while also considering the bioactive compounds in guava leaves.

Inhibitor efficiency (IE) quantifies the effectiveness of a corrosion inhibitor by measuring the reduction in corrosion rate when an inhibitor is applied, compared to an uninhibited system. It provides a percentage-based metric that indicates how much the inhibitor reduces corrosion activity on the metal surface. This method is widely used in corrosion science to assess and compare the performance of various inhibitor materials (Jones, 1996).

The inhibitor efficiency was calculated using the following formula:

$$IE\% = \frac{C_o - C_i}{C_0} \times 100$$

Where:

C_o = Average corrosion rate of the controlled group

C_i = Average corrosion rate of the experimental group

	Controlled	Experimental
Average Corrosion Rates (mm/yr)	0.952406886	0.493488504
Inhibitor Efficiency (%)	48.18511797	

Table 4. *Average Corrosion Rates of the Controlled and Experimental Groups and their Inhibitor Efficiency.*

The calculated inhibitor efficiency of the biowaste coating composed of guava (Psidium guajava) leaves and eggshell powder was found to be 48.19%. This value was derived by comparing the average corrosion rates of the coated and uncoated mild steel samples after immersion in geothermal water. The result indicates that the application of the biowaste coating was able to reduce nearly half of the corrosion experienced by the uncoated samples.

This level of efficiency suggests that the natural compounds present in guava leaves and the calcium content in eggshells contributed to the protective barrier formed on the metal surface, thereby slowing down the corrosion process. The outcome supports the potential of biowaste materials as promising alternatives to conventional chemical corrosion inhibitors, especially in environmentally sensitive settings.

5.2 Statistical Analysis

To determine whether the application of the guava leaf and eggshell-based coating significantly affected the corrosion rate of mild steel samples, a Welch's t-test (also known as the unequal variances t-test) was conducted. This test was chosen over the traditional Student's t-test due to the possibility of unequal variances between the coated and uncoated groups, a common occurrence in small or natural-sample experiments where homogeneity of variance cannot be assumed (Ruxton, 2006). Welch's t-test is well-suited for analyzing two independent samples with unequal sample variances and/or sample sizes, providing robust and reliable results even when assumptions of normality and equal variance are not fully met.

The following hypotheses were tested:

- *Null Hypothesis (H_0):* There is no significant difference in the corrosion rates between coated and uncoated mild steel samples ($\mu_1 = \mu_2$).
- *Alternative Hypothesis (H_1):* There is a significant difference in the corrosion rates between coated and uncoated mild steel samples ($\mu_1 \neq \mu_2$).

A two-tailed test was performed at a 0.05 level of significance ($\alpha = 0.05$), a conventional threshold in scientific research that balances the risk of Type I and Type II errors while maintaining statistical rigor (Kim, 2017). The test was conducted using Microsoft Excel, which calculated the test statistics, degrees of freedom, and corresponding p-value.

The statistical output indicated a p-value of less than 0.05, allowing the rejection of the null hypothesis. This suggests that the coating significantly reduced the corrosion rate of mild steel in geothermal water, confirming the effectiveness of the natural inhibitor composed of guava leaf extract and eggshell powder.

	Controlled	Experimental
Mean (mm/year)	0.952406885610777	0.493488504250231
Variance	0.0551598502186959	0.00803464435522072
Standard Deviation	0.234861343	0.089636178
Sample Size (n)	20	20

Table 5. *Comparative Corrosion Rate Statistics for Coated and Uncoated Samples.*

As shown in Table 5.4.1, the control group (uncoated mild steel) exhibited a mean corrosion rate of 0.9524 mm/year, while the coated group (treated with guava leaf and eggshell extract) had a significantly lower mean of 0.4935 mm/year. The standard deviations of the control and coated samples were approximately 0.2349 and 0.0896, respectively, indicating greater consistency in the corrosion resistance of the coated samples.

Statistic	Value
Degrees of Freedom (df)	24
t Statistic	8.16414723994617
p-value (two-tailed)	$2.19882104237518 \times 10^{-8}$
t Critical (two-talied)	2.06389854735026
Significance Level (α)	0.05
Decision	Reject H_0

Table 6. *Inferential Statistics Summary: Welch's t-Test.*

The Welch's t-test yielded a t-statistic of 8.1641 and a two-tailed p-value of 2.20×10^{-8}, which is far below the chosen significance level ($\alpha = 0.05$). The critical t-value for the two-tailed test was 2.0639, indicating that the computed t-statistic exceeds the threshold for statistical significance. Therefore, the null hypothesis was rejected, and it was concluded that the coating significantly reduced the corrosion rate of mild steel in geothermal water.

These results are further visualized in Figure 1, which displays a bar graph comparing the mean corrosion rates of the two groups with standard deviation error bars. Statistical evidence supports the effectiveness of the biowaste coating in corrosion inhibition.

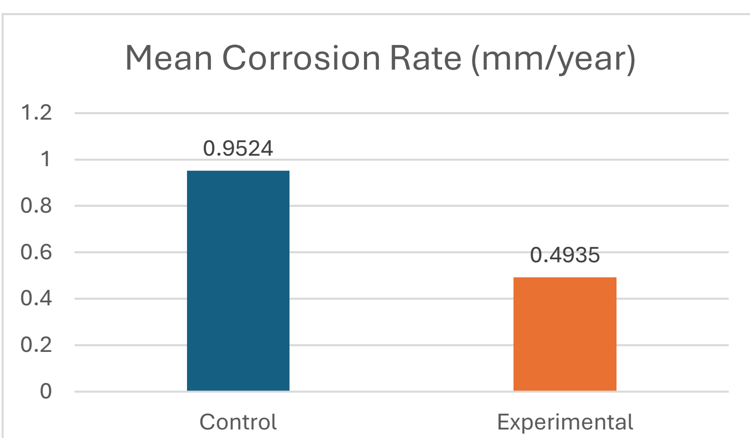

Figure 1. *Comparison of Mean Corrosion Rates Between Control and Coated Mild Steel Samples.*

Figure 1 illustrates the mean corrosion rates, measured in millimeters per year (mm/year), for uncoated (control) and coated (experimental) mild steel samples after exposure to geothermal water. The control group exhibited a higher mean corrosion rate of 0.9524 mm/year, while the experimental group, treated with the biowaste-based corrosion inhibitor composed of guava leaf extract, eggshell powder, and cornstarch binder, showed a significantly lower mean corrosion rate of 0.4935 mm/year. The notable reduction in corrosion rate demonstrates the coating's effectiveness in slowing down metal degradation under acidic and high-temperature geothermal conditions.

5.2.1 Analysis of Guava Leaf Performance

Guava leaf extract proved to be an effective natural corrosion inhibitor for mild steel in acidic environments based on the results of this study. The bioactive compounds present in guava leaves, such as flavonoids and tannins, facilitate adsorption onto the steel surface, forming a protective barrier that significantly reduces metal dissolution. According to the experimental data, samples treated with guava leaf extract showed a clear reduction in weight loss and corrosion rate compared to the uninhibited control samples, with inhibited efficiencies indicating substantial corrosion rate decreases across multiple trials.

Visual surface inspections further confirmed that the treated samples exhibited noticeably less rust formation and surface degradation, demonstrating the protective properties of the extract. Although some variability in inhibition efficiency was observed, likely due to differences in extract concentration or experimental conditions such as solution pH and exposure time, the overall trend clearly supports the extract's corrosion-inhibiting capability. These findings highlight guava leaf extract as a promising, eco-friendly, and cost-effective alternative to conventional synthetic inhibitors, with significant potential for industrial applications in acidic corrosion control.

5.2.2 Analysis of Eggshell Performance

The use of eggshell extract as a natural corrosion inhibitor demonstrated significant potential in reducing the corrosion rate of mild steel in an acidic environment. In two out of three trials, the inhibitor showed high effectiveness, achieving inhibition efficiencies of 47.1% and 52.7%, which indicates a substantial reduction in the corrosion rate compared to the uninhibited samples. This rate reduction suggests that the eggshell extract effectively slows down the metal dissolution process by forming a protective barrier on the steel surface. The high calcium carbonate ($CaCO_3$) content in eggshells is primarily responsible for this protective layer, which limits the direct interaction between the metal and the corrosive acidic medium. Additionally, organic compounds present in the eggshell membrane, such as proteins and amino acids, may enhance adsorption onto the metal surface, strengthening the barrier effect.

Visual surface inspection of the steel samples after immersion further supported these findings: the inhibited samples showed noticeably less rust formation and surface degradation compared to the heavily corroded control samples. However, one trial exhibited a negative inhibition efficiency, where corrosion was more severe with the present inhibitor. This inconsistency could be due to variations in extract concentration, poor dispersion, or incomplete surface coverage, emphasizing the need for standardized preparation methods.

Despite this, the overall results indicate that eggshell extract serves as an effective, low-cost, and environmentally friendly corrosion inhibitor with promising protective properties. Further research should focus on optimizing inhibitor formulation and evaluating its performance under different environmental conditions to maximize its industrial applicability.

5.3 Limitation Encountered

Several limitations were encountered during the experiment that may have influenced the accuracy, consistency, and long-term viability of the results. One of the primary limitations was the lack of access to high-precision laboratory equipment. Constraints such as limited availability of analytical balances and advanced surface characterization tools may have introduced minor inaccuracies in weight loss measurements and hindered a deeper assessment of corrosion mechanisms. Visual inspections, although useful for general observations, provided only superficial evaluations and lacked the resolution and analytical capabilities of advanced tools such as Scanning Electron Microscopy (SEM) or Fourier-Transform Infrared Spectroscopy (FTIR) (Kumar et al., 2020).

Inconsistencies during the preparation phase also affected the uniformity of the corrosion inhibitor mixture. Variations in drying time, grinding fineness, and the concentration of guava leaf extract and eggshell powder likely contributed to differences in inhibition performance between samples. Furthermore, the manual application of the coating resulted in uneven or incomplete surface coverage on some mild steel nail samples, which may have led to inconsistent protection and localized corrosion rates (Verma et al., 2018).

Environmental factors during the immersion process, including minor fluctuations in ambient temperature and pH levels of the geothermal water, were not tightly controlled. These variations could have influenced corrosion behavior and the performance of the coating. Additionally, the natural surface irregularities of the mild steel samples may have impacted coating adhesion and distribution, further contributing to variability in results (Saji & Thomas, 2015).

A particularly significant limitation was observed post-experiment regarding the stability of the corrosion inhibitor mixture. Approximately ten days after preparation, the mixture began to degrade at room temperature, exhibiting softening, phase separation, and a slight foul odor. This degradation occurred even without immersion, suggesting instability inherent to the formulation. The likely cause was the high moisture sensitivity of the cornstarch binder. Cornstarch, composed mainly of amylose and amylopectin, is inherently hydrophilic and tends to absorb moisture from the environment, leading to swelling, softening, and eventual liquefaction of the material (Mali et al., 2005; Shah et al., 2016). Moisture readily penetrates the amorphous regions of starch, compromising the film's structure and weakening its binding capability over time (Nasir et al., 2021).

Compared to synthetic corrosion inhibitors, natural formulations like the one developed in this study tend to have a shorter shelf life due to the absence of stabilizing additives or chemical cross-linking agents (Werle, 2008). Without enhancements to the binder system, the product remains vulnerable to microbial activity, moisture uptake, and environmental degradation. These limitations highlight the need for improved material engineering to enhance the reliability, storage stability, and applicability of biowaste-based inhibitors in real-world scenarios.

Despite these challenges, the observed limitations present opportunities for improvement. Future studies should investigate material modifications such as cross-linking cornstarch with citric acid, a multifunctional organic acid capable of reacting with hydroxyl groups in polysaccharides. Citric acid has been shown to improve the mechanical strength and water vapor resistance of starch-based films, enhancing their overall durability and shelf life (Li, 2023; Ghanbarzadeh et al., 2010).

Exploring alternative binders such as gum arabic, lignin, and chitosan may also significantly improve the formulation's performance. Gum arabic, a plant-derived hydrocolloid, exhibits strong adsorption behavior and corrosion inhibition efficiency, with its phytochemical content and mineral composition contributing to improved adhesion and film integrity (Umoren et al., 2008; Azzouzi, 2021; Nawaz, 2020). Lignin, the second most abundant natural polymer, has been widely recognized for its adhesive, biodegradable, and water-resistant properties making it a promising replacement for synthetic binders (Frihart, 2005; Mili et al., 2021). Similarly, chitosan, a biopolymer derived from chitin, is known for its biocompatibility and resistance to water-induced degradation. It has demonstrated excellent potential in improving the mechanical properties and durability of natural coatings, even at low concentrations (Kaczmarek & Sionkowska, 2018; Aguilar et al., 2016).

CHAPTER VI

Conclusion and Recommendation

This study aimed to explore a sustainable approach to corrosion inhibition by utilizing biowaste materials in the formulation of a natural coating. The following sections summarize the key findings, assess the limitations encountered, and provide recommendations for improving the formulation and extending its application. These insights contribute to the ongoing development of eco-friendly corrosion control methods in geothermal environments.

6.1 Summary of Findings

This study evaluated the corrosion-inhibiting potential of a natural coating made from guava (Psidium guajava) leaf extract and eggshell powder, using cornstarch as a binder. The coating was applied to mild steel samples and exposed to geothermal water for five days. Corrosion performance was assessed through weight loss measurements and corrosion rate calculations. The results showed a significant reduction in corrosion among coated samples compared to uncoated controls, with an average inhibition efficiency of 48.19%.

Statistical analysis using Welch's t-test confirmed the difference in corrosion rates was significant, indicating that the biowaste-based coating was effective in mitigating corrosion under short-term immersion. The guava leaf extract, rich in tannins and flavonoids, likely contributed through surface adsorption, while the calcium carbonate in eggshells served as a passive barrier. These results affirm the short-term protective capabilities of the coating.

6.2 Conclusions

Although the biowaste coating demonstrated short-term corrosion inhibition, it presented a notable limitation in terms of stability. Approximately ten days after preparation, while stored at room temperature, the coating mixture degraded and liquefied, making it unusable for further application. This degradation occurred even without immersion in geothermal water, indicating that the instability was intrinsic to the formulation itself. Cornstarch, the binder used in this study, is known to be highly hygroscopic and prone to microbial degradation or enzymatic hydrolysis when left unprotected and exposed to ambient moisture (Mali et al., 2005; Shah et al., 2016).

Without the addition of preservatives, cross-linkers, or drying treatments, starch-based systems tend to lose structural integrity over time. This behavior likely led to the observed liquefaction, as the film matrix broke down and the solid components separated. Thus, while effective as an inhibitor shortly after preparation, the coating lacks the necessary shelf life for practical or industrial use in its current form.

6.3 Limitations

One major limitation of this study was the post-preparation instability of the coating. Although the mixture performed well during the five-day immersion period, it liquefied roughly ten days after its initial preparation on June 9, even while stored at room temperature and not immersed. This limits its usability to a very short window after preparation, making large-scale or delayed application impractical. The likely cause is the cornstarch binder, which, being hydrophilic and biodegradable, is vulnerable to moisture uptake and microbial or enzymatic activity over time, especially in humid environments.

Additionally, variability in coating thickness and drying time may have influenced adhesion and performance. Equipment limitations restricted surface-level analysis, and the study did not simulate geothermal field conditions such as temperature cycling, flow dynamics, or pressure changes. Lastly, the corrosion test was limited to five days, which restricts conclusions about long-term inhibitor behavior.

6.4 Recommendations

To improve the stability and functionality of the coating, several modifications are recommended. First, the incorporation of natural cross-linkers such as citric acid or borax can enhance the thermal and water resistance of starch-based binders, increase shelf life and reduce degradation (Liu et al., 2009).

Second, adding plasticizers like glycerol or sorbitol in optimized amounts may improve film flexibility while slowing microbial breakdown. Future formulations could explore alternative natural binders such as chitosan, alginate, or cellulose derivatives, which have demonstrated better long-term stability under ambient conditions (Nair et al., 2018). Drying and curing the coating immediately after preparation may help minimize premature liquefaction. Storage in sealed, moisture-resistant containers with refrigeration can also delay degradation. For research purposes, testing immersion for longer durations (10–30 days) and under simulated geothermal plant conditions—such as dynamic fluid flow and temperature variations—would provide better insight into real-world applicability.

Lastly, further investigation of other biowaste materials like banana peel, coconut husk, or sugarcane bagasse is encouraged, as these may offer better structural or chemical synergy with natural binders. By addressing the identified formulation weaknesses, this research can serve as a basis for developing more robust, shelf-stable, and scalable green corrosion inhibitors.

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APPENDICES

Product Documentation

Figure 3. *Fresh guava leaves prepared for drying using a laboratory oven. This step was done to reduce moisture content and preserve the bioactive compounds.*

The image shows several pieces of fresh guava leaves spread evenly on a clean surface. The leaves appear green and intact, with visible veins and natural texture. The guava leaves are ready to be placed in a blender.

***Figure 4**. Collected eggshells after thorough cleaning and complete drying, ready for grinding. Eggshells serve as a calcium-rich component in the formulation.*

The image displays a collection of clean, dry eggshells on a tray. The shells are visibly free from membrane residues and moisture, with a uniform off-white color. Their brittle and porous texture suggests they are ready for grinding as part of the preparation process. The photo highlights the eggshells as a natural, calcium-rich material intended for use in the corrosion inhibitor formulation.

Figure 5*. Guava leaves placed inside a blender to be ground into finer particles for easier extraction of the active constituents.*

The image shows a view of a blender containing pieces of guava leaves. The leaves are visibly cut and positioned within the blender jar, ready for processing. The setup suggests preparation for particle size reduction, with the goal of making the plant material finer and more suitable for extraction. The surrounding environment indicates a laboratory setting.

Figure 6. *Ground guava leaves mixed with distilled water and subjected to boiling for 40 minutes to extract the plant's natural phytochemicals with corrosion-inhibiting properties.*

The image shows a mixture of finely ground guava leaves submerged in distilled water inside a cooking pot. The mixture appears dark green to brown in color, indicating the early stage of extraction. Steam or bubbling may be visible, suggesting that the solution is being heated. The setup reflects the preparation of a natural extract under controlled heating conditions.

Figure 7. *Continuous boiling of the guava mixture under moderate heat to ensure complete extraction of the active compounds.*

The image captures the guava leaf mixture in an active state of boiling. Bubbles and steam are visible on the surface, indicating sustained heat application. The mixture appears darker in color, suggesting concentration of the extract. The container is situated on a heat source, kitchen setting, as part of the extraction process.

Figure 8. *The boiled guava extract is strained using cheesecloth to separate the solid residues and obtain the liquid extract.*

The image shows the guava extract being poured through a piece of cheesecloth to filter out solid residues. The cloth is positioned over a container to collect the liquid portion of the extract. The setup highlights the separation process, with visible plant solids retained on the cloth and the darker liquid extract passing through below.

Figure 9. *Dried eggshells crushed manually using a mortar and pestle to produce a fine powder for blending into the inhibitor formulation.*

The image shows dried eggshells being ground into smaller pieces with a traditional mortar and pestle. Fragments of the shells are visible inside the mortar, with some already reduced to a coarse or powdery texture. The setup emphasizes the manual preparation of eggshell powder for incorporation into the corrosion inhibitor mixture.

Figure 10. *Cornstarch is measured as a natural binder to help hold the components of the corrosion inhibitor together.*

The image shows a measured amount of cornstarch placed in a container and a weighing scale beside. The fine, white powder is arranged neatly, indicating preparation for mixing. Cornstarch serves as the binder in the corrosion inhibitor, helping to combine and hold the guava extract and eggshell powder in a cohesive formulation.

Figure 11. *Addition of warm distilled water to the cornstarch to create a smooth binder solution.*

The image depicts warm distilled water beside a container holding cornstarch. The mixture appears in the process of being stirred or dissolved, with the goal of creating a uniform, smooth solution. The setup highlights the preparation of the binder that will be used to combine the active components of the corrosion inhibitor.

Figure 12. *The three key ingredients—guava extract, ground eggshells, and cornstarch binder—are gathered prior to final mixing.*

The image shows the three main components of the corrosion inhibitor formulation arranged separately in individual containers. The guava extract appears as a dark liquid, the ground eggshells as a fine white powder, and the cornstarch binder as a smooth, viscous solution. This setup represents the preparation stage just before combining all ingredients into a single mixture.

Figure 13. *All components are mixed thoroughly and stirred continuously for 10 minutes to achieve a homogeneous corrosion inhibitor mixture.*

The image shows the guava extract, ground eggshells, and cornstarch binder combined in a single container. A stirring tool is visible, indicating continuous mixing. The mixture appears uniform in texture and color, reflecting the thorough blending process carried out over 10 minutes to ensure even distribution of all components.

Figure 14. *The final corrosion inhibitor product, ready for application or testing. This mixture is expected to slow down the corrosion process based on the synergistic effect of guava leaves and eggshells.*

The image displays the completed mixture of guava extract, ground eggshells, and cornstarch binder in a container. The product has a thick, uniform consistency, indicating it is fully blended and ready for use. This natural formulation is intended for application on mild steel surfaces to reduce corrosion, utilizing the combined protective properties of its biowaste components.

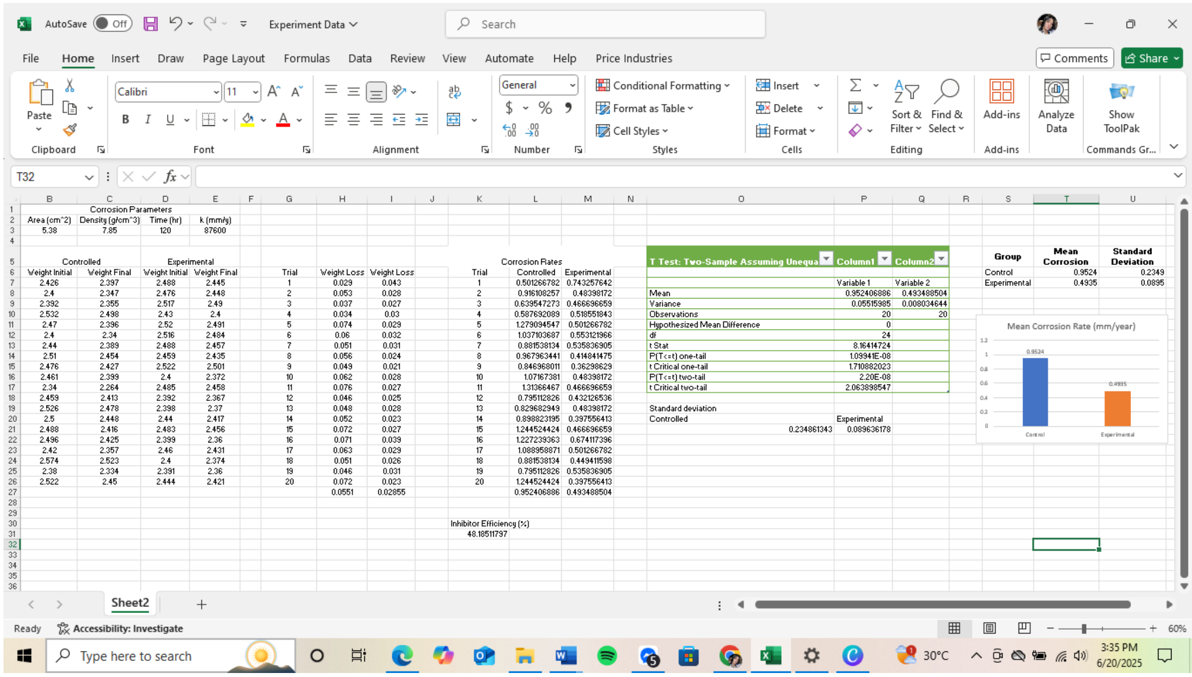

Figure 15. *Summary of the calculations and statistical analysis using Microsoft Excel.*

This figure displays the spreadsheet used to compute weight losses (g), corrosion rates (mm/year) and inhibition efficiencies (%) for both control and experimental mild steel samples. The calculations were based on the data of the initial and final weight of the metal samples that are collected after immersion in geothermal water for five days. Excel was utilized to organize the raw data, apply weight loss and corrosion rate formulas, as well as perform statistical summaries. This documentation ensures transparency and reproducibility of the results by showing the step-by-step computational process used in the study.

CURRICULUM VITAE

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Negros Oriental State University – Dumaguete City, Philippines
Bachelor of Science in Geothermal Engineering
2022 – Present

Santander National High School
Junior High School
2020

Lyceum of Cebu Inc.(Santander Campus)
Senior High School - STEM Strand
2022

TECHNICAL SKILSS

Basic Skills & Interests

- Problem Solving and Critical Thinking

SEMINARS ATTENDED

- GE Forum–"Geothermal Experience in Kenya", Philippine Association of Geothermal Engineering Students NORSU CEA, March 27, 2025
- GE Forum–"Industry Insight and Opportunities", Philippine Association of Geothermal Engineering Students NORSU CEA, April 22, 2025
- Nuclear Symposium, Department of Energy– May 28, 2025

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2022 – Present

Sibulan National High School
Junior High School
2020

Sibulan Science High School
Senior High School - STEM Strand
2022

TECHNICAL SKILSS

Basic Skills & Interests

- Microsoft Office (Word, Excel, PowerPoint) – Proficient
- Google Workspace – Proficient

Laboratory Skills

- Use of laboratory ovens, balances, and glassware for sample preparation
- Data collection and recording from experimental setups

Interests

- Sustainable energy solutions
- Fieldwork

SEMINARS ATTENDED

- Geothermal Engineering Forum 2025 – Industry Insights and Opportunities
- Geothermal Engineering Forum 2025 – Geothermal Experience in Kenya
- Department of Energy Nuclear Energy Symposium
- National Youth Summit 2024
- Batang Kaparis ni Rizal (BATARIZ) Program – DILG Region 7

- Dumaguete Youth Congress
- Dumaguetnon Youth Encounter

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2020 – Present

Catherina Cittadini (St. Louis) School
Junior High School
2018

Dauin Science High School
Senior High School - STEM Strand
2020

TECHNICAL SKILSS

Basic Skills & Interests

- Basic CAD and Simulation tools
- Report Writing & Technical communication
- Problem Solving & Critical Thinking

Laboratory Skills

- Safety and PPE Compliance
- Sample collection and handling
- Water and Steam quality analysis

SEMINARS ATTENDED

- GE Forum – *"Geothermal Experience in Kenya"*, Philippine Association of Geothermal Engineering Students NORSU CEA, March 27, 2025
- GE Forum – *"Industry Insight and Opportunities"*, Philippine Association of Geothermal Engineering Students NORSU CEA, April 22, 2025
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EDUCATION

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2022 – Present

Sagay National High School – Main Campus
Senior High School - STEM Strand
2022

Sagay National High School – Main Campus
Junior High School
2020

TECHNICAL SKILSS

Basic Skills & Interests

- Microsoft Office (Word, Excel, PowerPoint)

Laboratory Skills

- Data collection and recording from experimental setups

Interests

- Plumbing Planning
- First Responder (RCY Volunteer)

EXPERIENCES

- Red Cross Youth SNHS – MAIN Council, 2017-2022 – Member
- First Responder Sagay City Chapter, 2019-2021 – Member
- Philippine Red Cross Bacolod Chapter, 2021-2022 – Member

SEMINARS ATTENDED

- GE Forum – *"Geothermal Experience in Kenya"*, Philippine Association of Geothermal Engineering Students NORSU CEA, March 27, 2025

- GE Forum – *"Industry Insight and Opportunities"*, Philippine Association of Geothermal Engineering Students NORSU CEA, April 22, 2025
- Nuclear Symposium, Department of Energy – May 28, 2025
- Red Cross Youth Training 2017 – 2023
- Plumbing Installation Program – 2018
- First Responder Training – 2018
- Fire Rescue Training – 2018
- Invitational Training Philippine Red Cross Bacolod Chapter - 2020

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EDUCATION

Negros Oriental State University – Dumaguete City, Philippines
Bachelor of Science in Geothermal Engineering
2022 – Present

Foundation Preparatory Academy
Junior High School
2020

Ramon Teves Pastor Memorial-Dumaguete Science High School
Senior High School - STEM Strand
2022

TECHNICAL SKILSS

Basic Skills & Interests

- AutoCAD
- Microsoft Office (Word, Excel, PowerPoint) – Proficient
- Google Workspace – Proficient

Laboratory Skills

- Basic water quality testing (pH, conductivity)
- Use of laboratory ovens, balances, and glassware for sample preparation
- Data collection and recording from experimental setups

Interests

- Sustainable energy solutions
- Fieldwork and environmental site assessments

EXPERIENCE

Philippine Association of Geothermal Engineering Students – Internal Secretary
Dumaguete City, PH

- Organized internal communications between officers and committees, improving response time and task completion
- Managed digital records and archives of organizational documents for transparency and accountability
- Collaborated with executive board in planning student forums and technical webinars, boosting student engagement
- Drafted and reviewed internal memos, letters, and reports to support efficient organizational operations

Leadership & Activities

Sangguniang Kabataan (SK) - Member
Dumaguete City, PH
Barangay Calindagan, Dumaguete City – 2023 to Present

- Spearheaded youth development programs in coordination with local government units, benefiting over 200 young constituents
- Facilitated community outreach activities such as clean-up drives and youth forums promoting civic engagement
- Assisted in budget planning and resolution drafting for youth-related initiatives and infrastructure projects

Dumaguete Youth Volunteers Network - Member
Dumaguete City, PH
2023 to Present

- Participated in city-wide volunteer efforts focused on environmental sustainability, education, and disaster response
- Coordinated with fellow youth leaders to implement grassroots initiatives aligned with SDG goals
- Represented the organization in inter-agency meetings and local youth planning sessions

Local Youth Development Council (LYDC) – Member
Dumaguete City, PH
Dumaguete City – 2023 to 2026

- Collaborated with city youth organizations and the LYDO to craft the Local Youth Development Plan (LYDP)
- Provided insights and feedback on policies affecting education, employment, and health of Dumaguete's youth sector
- Promoted inclusive youth participation by helping bridge barangay-level initiatives with city-level strategies

Seminars and Trainings Attended

- Geothermal Engineering Forum 2025 – Industry Insights and Opportunities
- Geothermal Engineering Forum 2025 – Geothermal Experience in Kenya
- Department of Energy Nuclear Energy Symposium
- National Youth Summit 2024
- Batang Kaparis ni Rizal (BATARIZ) Program – DILG Region 7
- Local Youth Development Council Mandatory Training
- Dumaguete Youth Congress
- Dumaguetnon Youth Encounter

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EDUCATION

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2021 – Ongoing

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Senior High School Graduate Diploma – STEM Strand
(2019 – 2021)

- Graduated With High Honors

Junior High School Graduate Diploma – Special Science Class
(2015 – 2019)

- Graduated With High Honors

Guihulngan South Central School, Guihulngan City, Philippines
Elementary School Graduate Diploma
(2010 – 2015)

- Graduated With Honors
- Graduated within the top 1% percentile of the graduating class

TECHNICAL SKILSS

Basic Skills & Interests

- Graphic Design Software (Canva, Photoshop, etc.) – Proficient
- Microsoft Office (Word, Excel, PowerPoint) – Proficient
- Data and Statistical Analysis

Laboratory Skills

- Proficiency in laboratory sanitation and safety protocol execution
- Has experience utilizing precision laboratory equipment used for data gathering
- Familiarity with data collection and recording from experimental setups

Interests

- Environmental safety and waste reduction
- Sustainable and renewable energy
- Proper information dissemination and journaling
- Research and Developments towards system improvements in the field of engineering

SEMINARS ATTENDED

- Seminar on Student Researchers and Developing Research Publications, DOST, 2021
- Science Investigatory Project Conference (Guihulngan City Chapter), DepEd, 2021
- GE Forum – *"Geothermal Experience in Kenya"*, Philippine Association of Geothermal Engineering Students, 2025
- GE Forum – *"Industry Insight and Opportunities"*, Philippine Association of Geothermal Engineering Students, 2025
- Nuclear Symposium, Department of Energy, 2025

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