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EVALUATION OF LIME LEAF EXTRACT IN PINEAPPLE JUICE PROCESSING ENVIRONMENT AS A GREEN CORROSION INHIBITOR FOR MILD STEEL.

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Abstract -The study investigated the effectiveness of lime leaf extract (LiLE) as an environmentally friendly corrosion inhibitor for mild steel exposed to a pineapple juice processing environment. Mild steel specimens were prepared and immersed fully in fresh pineapple juice extract, either in the presence or absence of different concentrations of LiLE (0.1, 0.3, and 0.5 g/L). Investigation of the corrosion behavior was conducted using the weight loss technique with varying immersion times (12-72 h) and temperatures (25-45^{0}C). Characterization of the inhibitor and the corroded samples was done by FTIR and SEM analysis. From the results obtained, the corrosion rate declined with the increase in immersion time and inhibitor concentration. With an immersion time of 72 hours, the corrosion rate reduced from 4.90 mm/yr in the blank pineapple juice medium to 0.73 mm/yr in the inhibited medium with 0.5 g/L of LiLE, thus having an inhibition efficiency of 85.1%. Adsorption of the phytochemicals on the surface of mild steel was responsible for effective inhibition performance, which created an inhibitive barrier. From the FTIR analysis results, it is evident that the active functional groups, including hydroxyl, carbonyl, aromatic, amine, and nitro compounds, played a role in the inhibition adsorption process. SEM micrographs obtained from the uncontrolled media exhibited substantial surface degradation, in contrast to inhibited specimens, showing smooth, more compact surfaces with substantially reduced pitting and corrosion imperfections. Results indicate that the extract of the lime leaves is able to inhibit the process of corrosion effectively and can possibly be used as an inhibitor for mild steel in acidic food processing environments.

Keywords: Mild steel, corrosion inhibition, lime leaf extract, pineapple juice, FTIR, SEM, green inhibitor.

INTRODUCTION

Corrosion significantly affects the functionality, durability, and operational life of metallic materials commonly used in industrial and food processing conditions. Mild steel is still one of the most frequently employed engineering materials, due to its low cost -effectiveness, simplicity of manufacturing, potent mechanical features, and accessibility (Popoola, 2019). In addition, electrochemical degradation resulting from its interaction with aggressive environments often results in equipment failure, contamination risks, lower productivity, and higher maintenance costs (Verma et al., 2021; Holla et al., 2024).

In food processing industries, acidic food products cause severely corrosive environments for metallic components. Pineapple juice typically contains organic acids, dissolved oxygen, sugars, and other reactive constituents that promote metal breakdown and surface deterioration. Frequent exposure to such processing environments during processing can result in reduced performance and poor quality of the final product. Thus, improvement in corrosion resistance during the processing of fruit is still important to materials and corrosion studies.

Conventional corrosion mitigation approaches often involve the use of synthetic chemical

inhibitors. These inhibitors exhibit higher inhibition efficiencies; concerns regarding toxicity, environmental impact, disposal requirements, and regulatory restrictions have prompted the search for safer alternatives (Popoola, 2019; Sheydaei, 2024). Green corrosion inhibitors composed of plant-based substances have attracted progressively greater attention because they are essentially biodegradable, eco-friendly, acceptable for the environment, and usually affordable.

Plant-based extracts contain bioactive substances like alkaloids, flavonoids, tannins, terpenoids, polyphenols, saponins, and other oxygen- and nitrogen-containing elements capable of adsorbing onto the metal surface and producing protective layers against corrosive attack (Verma et al., 2021; Zakeri et al., 2022; Holla et al., 2024). Recent research work has shown that adsorption of bioactive activity lower both anodic dissolution and cathodic process, thereby lowering corrosion rate and enhancing surface coverage (Bandeira et al., 2025; Himeur et al., 2026).

Citrus-derived extracts have proven potential corrosion inhibition performance due to their prevalent bioactive substances and bioavailability. Extracts of lime leaves contain several bioactive substances that might help in adsorption and formation of a protective film on mild steel surfaces. The functional groups have the ability to interact with active metal sites and inhibit electrochemical corrosion processes. Furthermore, plant-based inhibitors align with current sustainability objectives and green manufacturing practices (Sheydaei, 2024; Bandeira et al., 2025).

Despite increasing interest in plant-based corrosion inhibitors, relatively limited information is available on the performance of lime leaf extract under conditions representative of pineapple juice processing. Most previous investigations on plant-derived inhibitors have focused on mineral acid environments such as hydrochloric and sulfuric acids rather than actual food-processing media. This creates a research gap in understanding the corrosion behaviour and effectiveness of plant extracts in complex acidic food-processing environments (Zakeri et al., 2022; Holla et al., 2024; Himeur et al., 2026).

Therefore, the focus of this research is on the effectiveness of lime leaf extract as a green corrosion inhibitor for mild steel in pineapple juice. The variables taken into account in determining the effect of the inhibitor are the concentration of the inhibitor, time of immersion, and the effect of temperature on corrosion. In addition, further tests such as FTIR and SEM were done in order to acquire information about the functional groups in the extract and the surface morphology of mild steel, respectively. The uniqueness of this study can be seen in the fact that the lime leaf extract was tested under conditions similar to pineapple processing.

MATERIALS AND METHODS

Sample Collection & Preparation

For the analysis of the mild steel, the chemical composition of the material in W% is as follows: C, 0.15; Mn, 1.26; V, 0.017; Si, 0.035; S, 0.008; Cr, 0.036; Ni, 0.03; Al, 0.083; Cu, 0.038; and Fe (balance). Analysis was performed at the Metallurgical Laboratory, Research and Development Centre (R&D Centre), Kaduna State. Spectromax was used with the model (MAXxLMF14) for chemical analysis. Mild steel sheet (MS) samples were sourced from Mechanical Village, Nsukka, Enugu State, Nigeria. Mild steel sheets were cut into dimensions of 2 x 3 x 0.25 cm. Drilling holes of 0.1cm diameter was done on the coupon ends in order to tie up the coupons using nylon thread. The Mild Steel coupons were polished using various grades of Emery paper from coarse to fine (1200). The samples were cleaned with distilled water and dried with acetone to prepare for the weight loss corrosion experiments. (Mbah et al., 2023).

Preparation of pineapple juice extract.

The Pineapple (*Ananas comosus*) fruits were purchased at New Market, Enugu, and the juice extraction was carried out at the Enugu State Polytechnic, Iwollo. The ripe fruits were cleaned properly using clean water to remove any impurities on the surface. The fruits were

peeled and cut into small pieces, and subsequently the juice was extracted by pressing at room temperature without heat treatment. The absence of heat treatment was necessary to preserve the natural acid composition and organic components of the juice. This ensured that the corrosive characteristics of the medium were not altered. The extracted juice was filtered through a 250 µm mesh strainer to remove fibrous materials and pulp. For each corrosion experiment, 100mL of the freshly prepared pineapple juice was used as the corrosive medium. The pH of the newly prepared pineapple juice was determined using a calibrated pH meter according to ASTM G51-95 (2012). A pH value of 3.24 was obtained, confirming the acidic nature of pineapple juice and its suitability as a corrosive environment for studies with mild steel (Ofoegbu, 2021). Its high acidity is mainly due to the organic acids like citric acid and ascorbic acid that help dissolve metals and produce hydrogen gas. This freshly extracted pineapple juice sample was used immediately after extraction to prevent any change in its composition due to oxidation or fermentation.

Plant sample collection, preparation and extraction

The Lime leaves were sourced from a garden within the premises of Enugu State Polytechnic. The extraction was done at Divine Chemical and Analytical Laboratory, Nsukka. Fresh lime leaves were washed with distilled water and dried at room temperature (27^0C) for 14 days before being ground into powder. The powdered lime leaves were transported to the laboratory (Divine Chemical and Analytical Laboratory, Nsukka) for extraction. A 500g quantity of dried powdered lime leaves was placed in a thimble and inserted into the Soxhlet extractor. 250ml of analytical-grade ethanol was poured into a round-bottom flask connected to the Soxhlet extractor and condenser (as shown in fig 3.1b), which was then placed on the isomantle. The side arm of the Soxhlet extractor was wrapped with glass wool. The solvent was heated at 60^0C for 3 hours. As the ethanol vapor passed into the side arm of the condenser, it condensed and got back into the sample contained in the thimble. The ethanol-soluble components would then be dissolved and siphoned back into the flask (fig 3.1b). Extraction was done for 3 hours. After extraction, the flask containing the extract was disconnected from the extraction equipment and heated at 40^0C for 4 hours to dry most of the ethanol, causing the extract to form a gel; the gel was cooled in a desiccator and weighed (Mbah et al., 2023). The final yield gotten was 36.4g.



Figure 1: (a) Powdered lime leaves and (b) Soxhlet extractor

Weight loss method

The weighed mild steel coupons recorded as (W_1) were suspended with nylon threads. Each coupon was completely immersed in 100 mL of pineapple juice contained in a separate beaker in both uninhibited and inhibited pineapple juice solutions.

The solutions were maintained under static conditions without external stirring throughout the designated immersion periods. After the designated time intervals, the mild steel samples were retrieved, soft brushed, washed with distilled water, and dried in air following immersion in acetone. Mild steel coupons were again weighed, and the weight values were noted as (W_2). All experiments were performed in triplicate, and the results were presented. The difference in weights ΔW for the uninhibited and inhibited solutions was calculated from equation (1). The total weight lost by the metal sample after each time interval is considered as the cumulative weight loss.

$$\Delta W = W_1 - W_2 \quad (1)$$

The corrosion rate CR (mm/yr) of the mild steel coupons in uninhibited and inhibited media, percentage of surface coverage (θ), and efficiency of inhibition (IE%) were determined by use of equations 2, 3, and 4 respectively;

$$\text{Corrosion Rate (mm/yr)} = \frac{K \times \Delta W}{A\rho t} \ldots.(2)$$

$$\text{Inhibition efficiency(I.E\%)} = \frac{CR_{(uninhib)} - CR_{(inhib)}}{CR_{(uninhib)}} \times 100\% \ldots(3)$$

$$\theta = \frac{CR_{(uninhib)} - CR_{(inhib)}}{CR_{(uninhib)}} \ldots. (4)$$

Where ΔW is the difference between initial weight (W_1) and final weight (W_2), A is area of the sample of mild steel coupon in cm^2, ρ is theoretical density of the mild steel = 7.85 g/cm^3 (Frederick et al., 2020), K is constant (87600), t is the exposure time, $CR_{(uninhib)}$ and $CR_{(inhib)}$ are the corrosion rate of mild steel absence and presence of inhibitor at the same process conditions, I.E is the inhibition efficiency and θ is surface coverage.

Effect of immersion time

The mild steel coupons were separately immersed in 500 mL beakers filled with 100 mL of uninhibited and inhibited solutions of pineapple juice at room temperature with various concentrations of inhibitor (0.1, 0.3, and 0.5 g/L). The mild steel coupons were withdrawn from the solutions at intervals of 12, 24, 48, and 72 hours (Aliyu and Ibrahim, 2021).

Influence of inhibitor concentration and temperature

The prepared mild steel coupons were weighed and dipped into uninhibited and inhibited solutions of LiLE at different concentrations (0.1, 0.3, and 0.5 g/L) at various temperatures of 25, 35, 40, and 45^0C. The final weight was obtained, and average weight losses were recorded. The inhibitor concentrations that had relatively high efficiencies were considered optimum concentrations (Vikas et al., 2017; Vashi & Prajapati, 2017).

Characterizations

FT-IR Analysis

The FT-IR spectroscopic technique was used to identify functional groups and chemical contents present in ethanolic lime leaf extract (LiLE). The analysis was performed at the Central Laboratory of the University of Nigeria, Nsukka, using a NICOLET IS5 FT-IR spectrophotometer (Thermo Scientific) over a wavenumber range of 4000-500 cm^{-1} (Hari & Vandana, 2019). The resulting spectrum was examined to identify functional groups that could potentially participate in adsorption onto the mild steel surface.

Scanning Electron Microscopy

Surface morphology was examined at the Metallurgical Laboratory, Research and Development Centre (R&Dc), Kaduna, Nigeria. Using a scanning electron microscope (Model: Prisma E, SN: 9954043) at an accelerating voltage of 10 kV. The SEM micrographs were used to examine the surface morphology of the mild steel specimens before and after immersion in pineapple juice in the absence and presence of lime leaf extract. Special attention was given to surface features

associated with corrosion attacks, including surface roughness, pits, cracks, pores, cavities, and protective films formed by inhibitors, providing insight into the morphology of corrosion attack and the effectiveness of LiLE as a corrosion inhibitor (Tsutsui et al., 2025).

RESULTS AND DISCUSSION

Effect of Immersion Time

The results obtained for the corrosion rates and inhibition efficiencies of mild steel in uninhibited and inhibited solutions are illustrated in Figures 2 and 3, respectively. The results revealed that the corrosion rate of mild steel at room temperature decreases with an increase in immersion time. With the lowest immersion time of 12 hours, the corrosion rates of mild steel in uninhibited and inhibited 100 mL pineapple juice solutions were 18.58mm/yr and 9.42 mm/yr, respectively. However, with the highest immersion time of 72 hours, the corrosion rate reduced to 4.90 and 0.73 mm/yr, respectively. The observed decrease in corrosion rate with increasing immersion time may be associated with the accumulation of corrosion products and/or the development of a partially protective surface film.

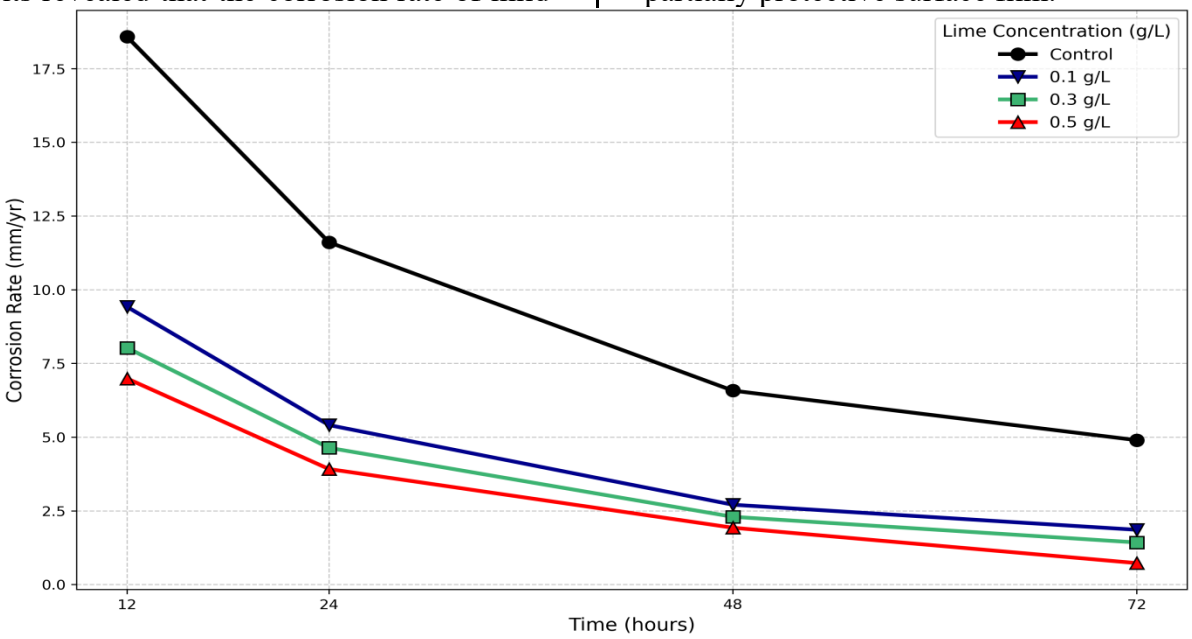


Figure 2: Effect of immersion time on the corrosion rate of mild steel in pineapple juice in the presence and absence of LiLE.

The non-linearity of the corrosion rates of the mild steel plots in the uninhibited medium implies that the mild steel corrosion is a heterogeneous process with several steps. These findings are consistent with those of Usman (2017). In general, a decrease in corrosion rate with time can be associated with changes in the exposed surface, accumulation of corrosion products, depletion of aggressive species near the surface, or development of partially protective films.

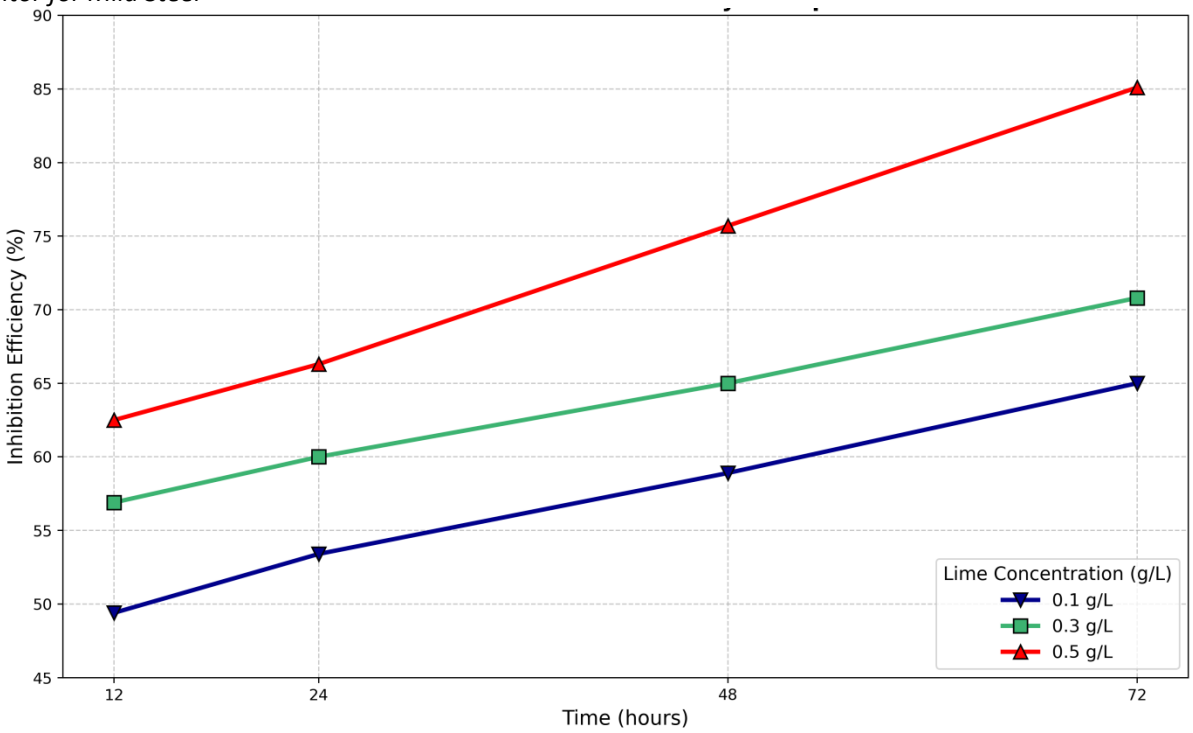


Figure 3: Effect of immersion time on the inhibition efficiency (I.E%) of mild steel in pineapple juice in the presence and absence of LiLE.

From the current study results, corrosion rate decreased from 4.90mm/yr for the uninhibited pineapple juice to 0.73 mm/yr in the presence of 0.5g/L LiLE at 72 hrs. The 85.1% maximum inhibition efficiency obtained from the addition of 0.5 g/L LiLE in 72 h indicates that lime leaf extract is a relatively efficient inhibitor in the pineapple juice solution. Relative to inhibition efficiency, this result is relatively comparable although slightly lower than the ones reported for some other green inhibitors of Citrus species used in very harsh acidic solutions. As per Haldhar et al. (2019), the maximum inhibition efficiency of 96.46% was recorded for Citrus aurantifolia leaf extract at 250 mg/L of concentration in 0.5 M H_2SO_4 through weight loss, potentiodynamic polarization, and electrochemical impedance spectroscopy methods. The effectiveness was explained by the adsorption of phytochemicals containing heteroatoms on the surface resulting in a blocking layer formation. Similarly, Hassan et al. (2016) obtained the inhibition efficiency of 89% for Citrus aurantium leaf extract at 1 M H_2SO_4 at 10 mL and 40^0C.

Also, the 85.1% efficiency achieved in the current study is similar to those of other citrus based inhibitors. For example, Citrus limetta peel extract (Sowmyashree et al., 2023) has been found to offer about 93% efficiency in inhibiting mild steel in hydrochloric acid, the inhibition being explained by a mixture of physical adsorption and chemical adsorption. In another study (Bolo et al., 2019), Citrus microcarpa leaf extract inhibited mild steel in 1.0 M HCl by 97.40% at the maximum concentration tested. This value is higher than that attained in the current study (85.1%); however, a careful comparison should be done since there are significant differences in the corrosive environment, inhibitor concentration, method of extraction, time of exposure, and temperature conditions.

The relatively lower efficiency observed for LiLE in the present study may therefore be associated with the nature of the corrosive environment. Unlike the mineral-acid media used in most published Citrus-inhibitor studies, the present investigation employed fresh pineapple juice, which contains organic acids and other constituents that can participate in the

corrosion process. The complex composition of a food-processing medium may influence both the aggressiveness of the environment and the adsorption behaviour of phytochemicals on the mild steel surface. Nevertheless, achieving 85.1% inhibition under these conditions indicates that LiLE has considerable potential as a green corrosion inhibitor for mild steel in food-processing environments. The observed improvement in surface morphology of the inhibited specimen relative to the uninhibited control further supports the formation of an adsorbed protective layer, as observed from the SEM analysis.

In general, this comparison shows that the inhibitive performance of LiLE falls within the same range as that of a number of plant extracts and Citrus-based corrosion inhibitors. While certain Citrus extracts have shown efficiencies exceeding 90% in mineral-acid media, the fact that an efficiency of 85.1% was reached in the pineapple juice medium is noteworthy since it represents the real-life conditions of the food processing industry.

Characterization

The FTIR spectrum of lime leaf extract (Figure 4) also displays well-defined absorption bands indicative of various functional groups. The characteristic peaks and their corresponding functional groups are summarized in Table 1.

Table 1: Characteristics of IR (LiLE) Absorption peaks of functional groups

Vibration	Peak Position (cm^{-1})	Intensity
Alcohols, phenols O-H stretch	3334.00	s
C-H stretch (aliphatic)	2852.23–2921.35	s
C=O (esters/carboxylic acids)	1732.36	s
C=C (aromatic rings) or N-H (amines), flavonoid/polyphenol	1608.93	s, m
C-H bending (aliphatic chains)	1455.22	s, m
NO_2 stretch (nitro compounds)	1375.85	s
Metal-ligand vibrations (M-O, M-S)	404.87–567.35	Hidden in fingerprint region

The FTIR spectrum of the lime leaf ethanolic extract (LiLE) shows a characteristic broad O-H stretch (3334.00cm^{-1}). Alcohols and phenols are confirmed by this; alkanes are confirmed by the C-H stretch (~2852.23-2921.35cm^{-1}); esters and carboxylic acids are confirmed by the C=O stretch (~1732.26cm-1). The presence of aromatic rings or amines is confirmed by the C=C or N-H stretch (~1608.93cm^{-1}). The existence of nitro compounds is confirmed by the NO_2 stretch (~1375.85cm^{-1}). The results suggest that lime leaves extract contains a hybrid inhibitor system combining carboxylic acids, aromatic rings, amines, and nitro compounds (NO_2) for active adsorption on mild steel, and natural polyphenols as eco-friendly additives (Hicham & Samah, 2017).

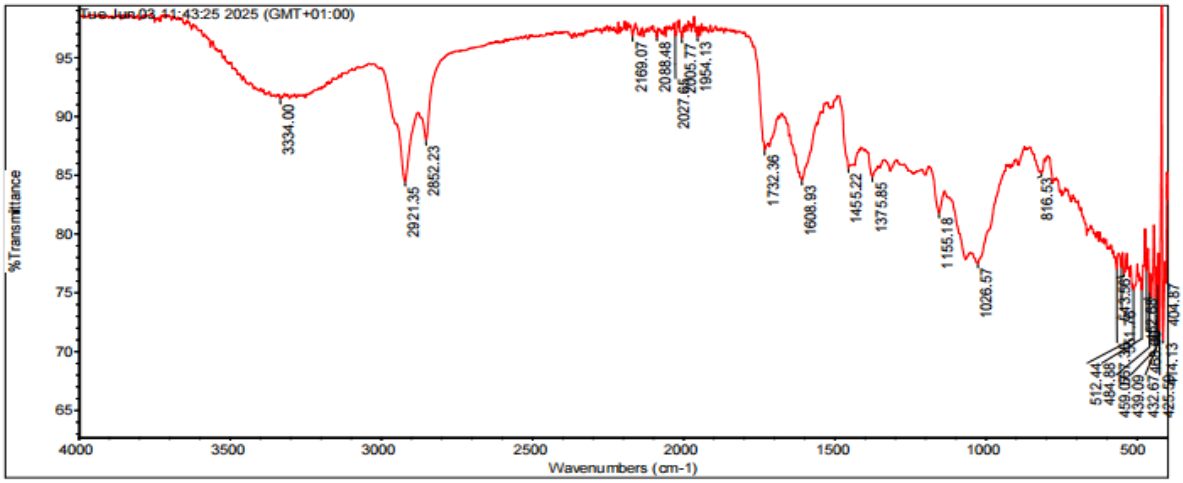
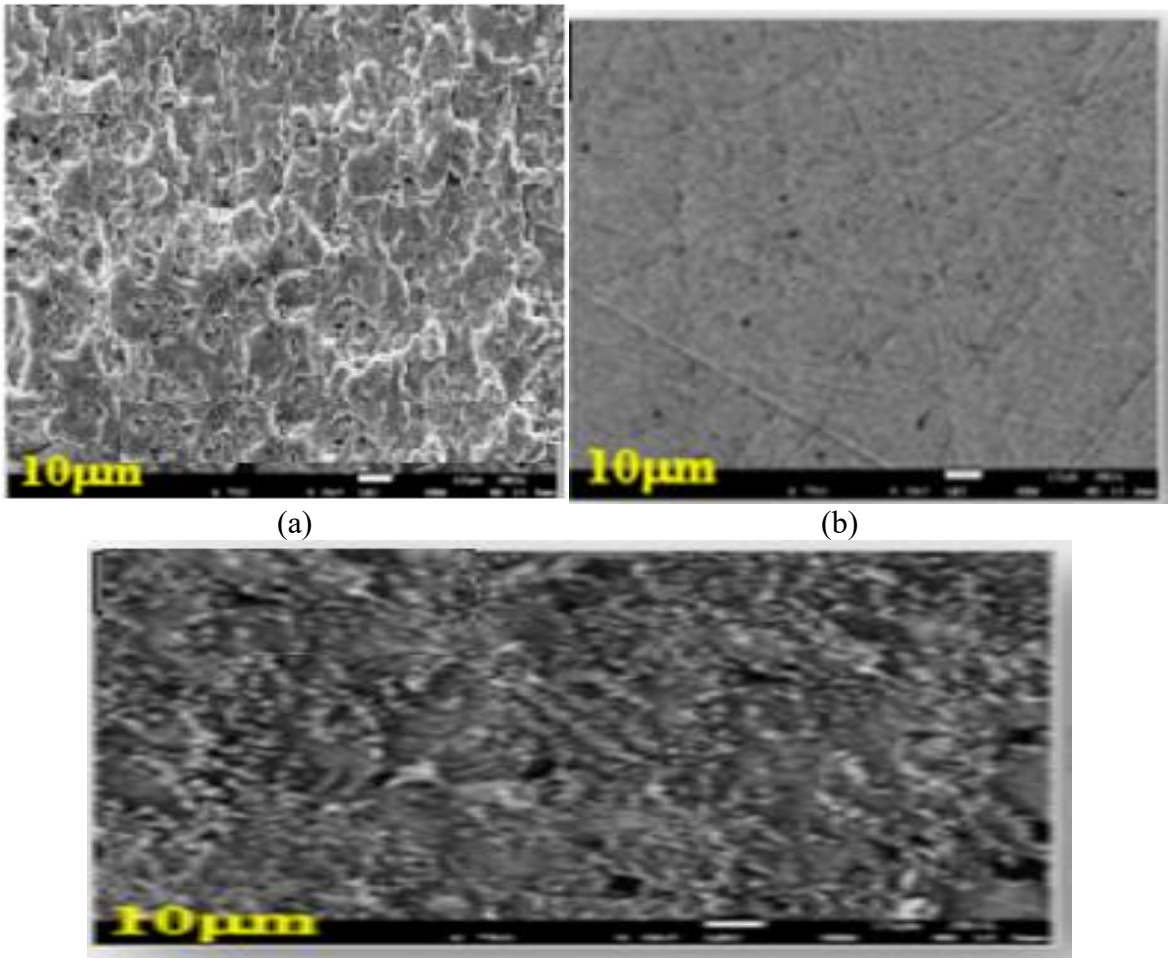


Figure 4: FTIR spectrum of Lime Leaf Extract (LiLE)

Scanning Electron Microscopy (SEM) Analysis

SEM images of mild steel specimens were illustrated in Figures 5a-c at 25^0C. The SEM image of the polished mild steel specimen prior to the immersion process (Figure 5a) showed that there were not many polishing marks on its surface, which proved that there was no prior corrosion damage. The polished fresh surface of the mild steel coupon was smooth, with few scratches produced by the SiC abrasive paper, indicating that the sample surface was initially free of corrosion defects and suitable for corrosion studies. However, after immersion in pineapple juice without an inhibitor (Figure 5b control), the surface morphology changed drastically. SEM microscopy demonstrates severe surface deterioration, characterized by pronounced roughness, cracks, pores, deep pitting, and cavities irregularly distributed across the surface. The corrosion products that formed on the mild steel surface were poorly adherent and provided no protection, as seen by the corrosion layer becoming porous rather than compact.



(a) (b)

(c)

Figure 5: SEM micrographs of mild steel: (a) polished surface before immersion; (b) surface after immersion in uninhibited pineapple juice; and (c) surface after immersion in pineapple juice containing 0.5 g/L LiLE at 25^0C.

The surface appearance of mild steel improved progressively with the increase in the concentration of the inhibitor. After adding 0.5 g of LiLE at 25^0C, the degree of corrosion was remarkably reduced, and there was a significant decrease in the number and depth of pitting corrosion. The surface appeared slightly smoother and more compact than the control.

Such improvement suggests that the bioactive constituents contained in the lime leaf extract were adsorbed on the surface of mild steel and formed a barrier layer on the surface of mild steel. It is known that the LiLE consists of bioactive constituents such as flavonoids, limonene, nitro compounds, linalool, and polyphenols, and other heteroatoms containing lone pairs of electrons and π electrons, which may interact with the surface of mild steel through adsorption processes (Verma et al., 2018).

CONCLUSION

The study aimed to examine the inhibitive effect of lime leaf extract on the corrosion of mild steel in pineapple juice. It was evident that adding LiLE greatly decreased the rate of corrosion compared to that of the uninhibited medium. At all concentrations studied, the inhibitive effectiveness increased with an increase in the concentration of the inhibitor. The highest value of 85.1% inhibition efficiency was achieved at 0.5 g/L LiLE for 72 h, with a decrease in corrosion rate from 4.90 mm/yr in the uninhibited pineapple juice to 0.73 mm/yr in the inhibited medium.

The FTIR technique showed the presence of certain functional groups such as hydroxyl, aliphatic C-H, carbonyl, and aromatic-related functional groups, which can possibly act as an adsorbent on the mild steel surface. The SEM investigation also revealed that the uninhibited sample had severe surface damage, while the surface of the LiLE-treated sample was comparatively smooth and undamaged.

The inhibition mechanism is mainly due to the adsorption of the phytoconstituents of LiLE on active sites of the mild steel surface.

From the findings of this experiment, one can deduce that the use of lime leaf extract can be considered a possible environmental corrosion inhibitor for mild steel in pineapple juice and other similar conditions in food processing. It shows potential as an environmentally friendly alternative to conventional corrosion inhibitors because of its natural origin and possibility of biodegradation. Further research on this topic with electrochemical methods, adsorption isotherms, surface chemistry studies, stability, and other parameters must be carried out.

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