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Corrosion Inhibitor for Printed Circuit Board using Papaya Leaves Extract

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Abstract

This study explores the potential of papaya leaf extract (PLE) as an eco-friendly corrosion inhibitor for copper in printed circuit boards (PCBs) immersed in sodium chloride (NaCl) solutions. A systematic approach was employed, starting with the preparation of PLE through extraction using 70% ethanol at 45°C for 2.5 hours. The efficiency of PLE as a corrosion inhibitor was evaluated by immersing copper PCBs in 1 M NaCl solutions with varying ratios of PLE (100% NaCl, 90% NaCl and 10% PLE, 70% NaCl and 30% PLE, and 50% NaCl and 50% PLE). Fourier Transform Infrared (FTIR) spectroscopy identified key functional groups in PLE, including O-H (~3400 cm^{-1}), C-H (~2900 cm^{-1}), C=O (~1700 cm^{-1}), and C=C aromatic vibrations (1600–1500 cm^{-1}), as well as C-O or C-N stretching (~1200–1000 cm^{-1}), indicative of polyphenols, flavonoids, and tannins, which adsorb onto the copper surface to inhibit corrosion. Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDX) showed a significant increase in copper content and a decrease in oxygen concentration with higher PLE concentrations and it also reduces surface roughness, minimizes pitting. The copper atomic percentage increased from 47.8% in pure NaCl (100% NaCl) to 84.0% in the solution containing 50% NaCl : 50% PLE, while oxygen content decreased from 26.2% to 10.8%. Electrochemical studies, including Tafel polarization and Nyquist impedance plots, demonstrated that PLE acts as a mixed-type inhibitor, reducing anodic and cathodic reactions and significantly enhancing charge transfer resistance. At the ratio mixture of 50% NaCl: 50% PLE, the copper surface exhibited maximum protection, with a dense and uniform inhibitor layer. These findings highlight the potential of PLE as an eco-friendly and sustainable corrosion inhibitor for copper in harsh environments.

1. Introduction

Corrosion is a serious issue that damages electrical components made of steel and copper, posing significant reliability problems for printed circuit boards (PCBs) and microelectronic devices [1]. Various methods, such as coating, cathodic protection, and anodic protection, have been employed to combat corrosion. Among these, the use of corrosion inhibitors is particularly noteworthy. In recent years, plant-based, eco-friendly inhibitors have emerged as a promising solution, offering effective corrosion prevention while minimizing environmental impact. [2]. Many studies have been conducted on Papaya leaf extract (PLE) as a corrosion inhibitor. Organic components in the extract can adsorb onto the metal surface, creating a protective layer and slowing down the pace of corrosion [3]. For PCBs and microelectronic devices, applying PLE offers a sustainable and effective method to enhance longevity and reliability, addressing both technical and environmental sustainability challenges.

Organic inhibitors for corrosion are essential additives used to protect metals from degradation in various environments. These inhibitors are typically natural or synthetic compounds that are environmentally friendly and biodegradable, making them suitable for a range of applications [4]. Organic corrosion inhibitors work by forming a protective layer on the metal surface, preventing corrosive substances from reaching the metal and slowing down the corrosion process. They contain electron donor atoms like phosphorus, sulphur, oxygen, and nitrogen, which allow them to be adsorbed onto the metal surface, providing protection against acidic and saline solutions [5].

Numerous research works have examined PLE's efficacy in preventing corrosion. Duplex (αβ) brass corrosion was suppressed by PLE in 1M nitric acid. According to [6], PLE slowed the pace at which mild steel corroded in acidic environments, with the effectiveness of the inhibition rising with temperature and concentration. The theory that PLE prevents corrosion by adsorbing inhibitor molecules onto the metal surface was further validated by Okafor and Ebens et al. employed PLE as an environmentally benign copper inhibitor in sulfuric acid (H2SO4) medium more recently. Results from X-ray photoelectron spectroscopy (XPS) and morphological examination showed that the extracted papaya leaves extract (PLE) had good anti-corrosion qualities within a specific temperature range. Cu-S and Cu-N bonds formed a protective coating on the copper surface, as shown by the XPS study [7].

This study aims to investigate the potential of papaya leaf extract (PLE) as a green corrosion inhibitor for copper in PCBs. Papaya leaves were chosen for this research due to their high content of bioactive compounds, which are known for their corrosion inhibition properties. By analysing its chemical properties and corrosion inhibition efficiency, this research seeks to determine whether PLE can provide an effective and sustainable solution for mitigating copper corrosion.

2. Materials and Methods

2.1 Preparation of Printed Circuit Board

PCB sheets were used, with a standard thickness of 1.57 mm. In this study, single-sided PCBs with a dimension of 5 cm by 7 cm are utilized. These boards are cut using a metal hand shear into 1x1 cm identical pieces as depicted in Fig. 1. Next, 600 grits of sand paper are used to remove Sn coating in order to obtain the copper surface. This surface is then washed with ethanol in order to remove any contamination, and this ensure that the sample surface is mainly cover by copper surface.

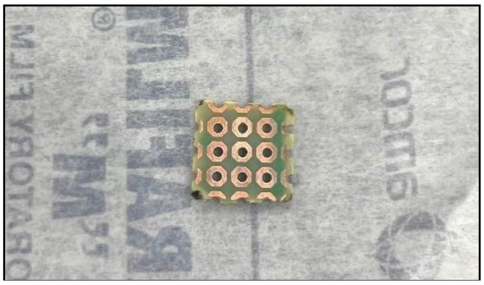

Fig. 1 A finished sample of PCB

2.2 Preparation of Papaya Leaves Extract

The preparation of papaya leaves extract involved several stages as shown in Fig. 2. Stage one involved the collection and washing of fresh papaya leaves with distilled water to remove contaminants such as dirt and dust.

In stage two, the washed leaves were placed in a shaded area to air-dry and avoid degradation from direct sunlight. After the air-drying process, the leaves were placed in an oven at 45°C for 32 hours to ensure complete dryness, which is essential for effective grinding and extraction.

Stage three involved grinding the dried leaves into a fine powder using a mechanical grinder. The powdered leaves were then sieved through a 250-micron mesh to achieve a uniform particle size, ensuring homogeneity for the extraction process.

In stage four, 50 grams of the sieved papaya leaf powder were immersed in 500 ml of 70% ethanol for the extraction of active compounds. The mixture was stirred continuously at 350 rpm using a magnetic stirrer for 2.5 hours while maintaining a temperature of 45°C. After stirring, the mixture was filtered using Whatman filter paper to separate the solid residues from the liquid extract.

Stage five involved concentrating the filtered ethanol solution using a rotary evaporator set to 45°C and 70 rpm. This process was carried out under low temperature and reduced pressure to evaporate the ethanol solvent, leaving behind a concentrated extract of papaya leaf compounds.

In stage six, the concentrated papaya leaf extract was stored in 10 ml amber glass bottles to protect it from light and prevent degradation. The extract was then ready for further analysis using FTIR spectroscopy, to identify its functional group.

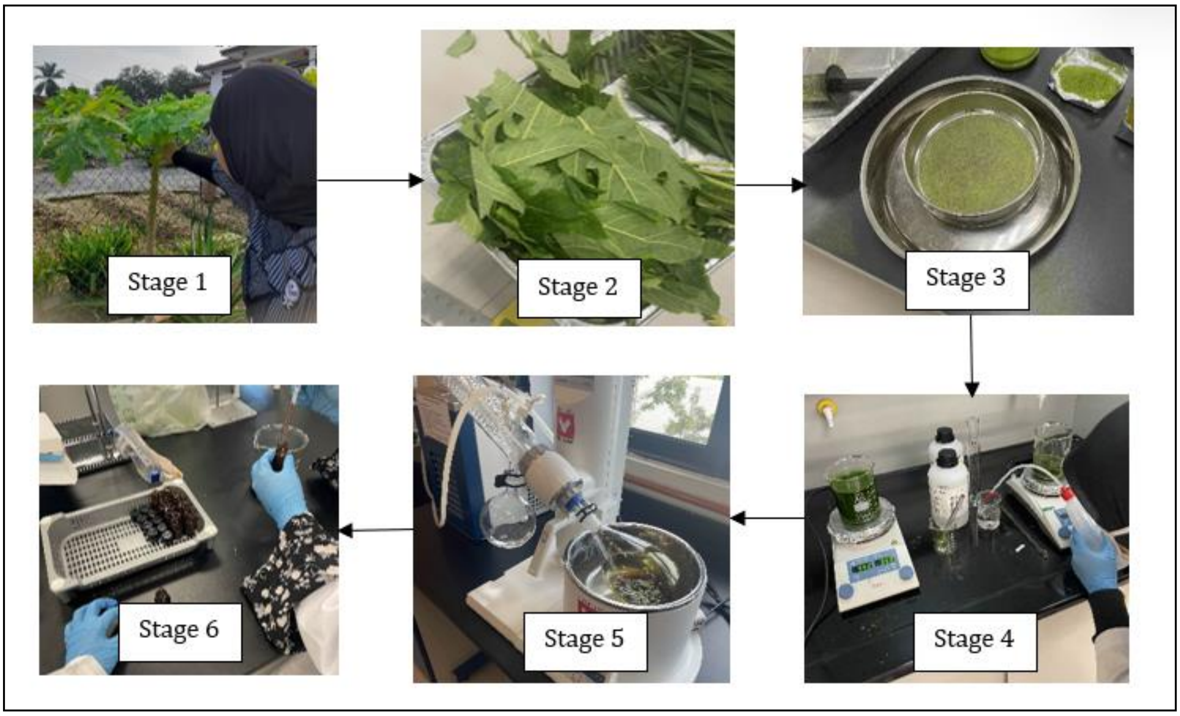

Fig. 2 Flow process of papaya leaves extraction

2.3 Preparation for a solution for immersion test using various ratio of NaCl and PLE composition

A 1 M sodium chloride (NaCl) stock solution was prepared by dissolving 58.44 g of NaCl in distilled water and diluting the mixture to a final volume of 1 litre. This stock solution was used as the base to create different ratios of NaCl and papaya leaf extract (PLE). The mass was calculated by following the equation (1).

$$Mass\ of\ NaCl\ (g) = Molarity\ (M) \times Volume\ (L) \times Molar\ Mass\ of\ NaCl\ (g/mol) \quad (1)$$

The preparation of NaCl solutions with varying PLE ratios involved combining specific volumes of the NaCl stock solution and PLE. For each ratio, 25 ml of solution was prepared and placed in test tubes as shown in Fig. 3. Four different concentrations were prepared: 100% NaCl, 90% NaCl with 10% PLE, 70% NaCl with 30% PLE, and 50% NaCl with 50% PLE.

In order to achieve the desired concentrations, 22.5 ml of NaCl solution was mixed with 2.5 ml of PLE for the 90% NaCl and 10% PLE solution. For the 70% NaCl and 30% PLE solution, 17.5 ml of NaCl solution was combined with 7.5 ml of PLE. For the 50% NaCl and 50% PLE solution, equal volumes of 12.5 ml each of NaCl solution and PLE were mixed.

Fig. 3 Containment of NaCl solutions with varying concentrations of PLE

2.4 Immersion test

Four PCB sample were prepared for the immersion test, with each board submerged as depicted in Fig. 4 in NaCl solutions containing varying concentrations of papaya leaf extract (PLE): 100% NaCl, 90% NaCl with 10% PLE, 70% NaCl with 30% PLE, and 50% NaCl with 50% PLE. Each PCB was placed in 25 ml of the corresponding solution in separate beakers. The immersion test was conducted over 7 days, during which the samples were observed for any visible signs of corrosion.

At the end of the immersion period, the samples are taken out and rinsed with distilled water to eliminate deposit from corrosion product and then dried to the air. The dried samples were then transferred into sol-gel container, ensuring stability and preventing further oxidation or contamination prior to analysis.

Subsequently, the coated samples underwent SEM EDX and EIS analysis for morphology and corrosion rate analysis.

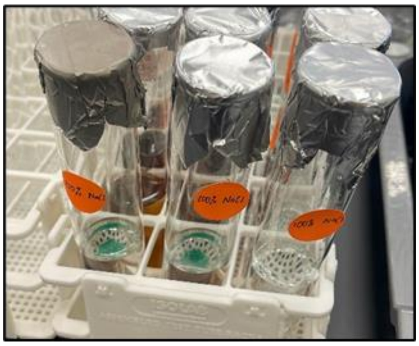

Fig. 4 Immersion of PCB in NaCl solutions with varying concentrations of PLE

3. Results and Discussion

3.1 Functional Group Analysis using FTIR

The superimposed FTIR spectra of distilled water and papaya leaf extract (PLE), as depicted in Fig. 5, reveal that the PLE solution is mainly contained with several functional group. In order to confirm the functional group produce by the PLE solution, a comparison between FTIR spectrum this solution and the distilled water is carried out. A comparison between both FTIR spectrum reveal that the spectrum of distilled water predominantly displays peaks corresponding to O-H stretching vibrations (~3400 cm^{-1}) and bending vibrations (~1600 cm^{-1}), confirming its composition as pure water devoid of significant organic functional groups. Conversely, the PLE spectrum exhibits a range of peaks indicative of bioactive compounds. Notable peaks include O-H stretching (~3400 cm^{-1}), C-H stretching (~2900 cm^{-1}), C=O stretching (~1700 cm^{-1}), C=C aromatic vibrations (1600–1500 cm^{-1}), and C-O or C-N stretching (~1200–1000 cm^{-1}), reflecting the presence of polyphenols, flavonoids, tannins, and other oxygen- or nitrogen-based functional groups [8].

The comparison between the FTIR spectra of distilled water and papaya leaf extract (PLE) helps identify the active compounds in PLE that contribute to its corrosion-inhibiting properties. Distilled water serves as a baseline, showing only typical water peaks, while the PLE spectrum reveals distinct peaks for functional groups like O-H, C-H, C=O, C=C, and C-O or C-N stretching, which indicate the presence of bioactive compounds such as polyphenols, flavonoids, and tannins. This comparison highlights the unique chemical components in PLE that can potentially form protective layers on metal surfaces, making it a promising corrosion inhibitor.

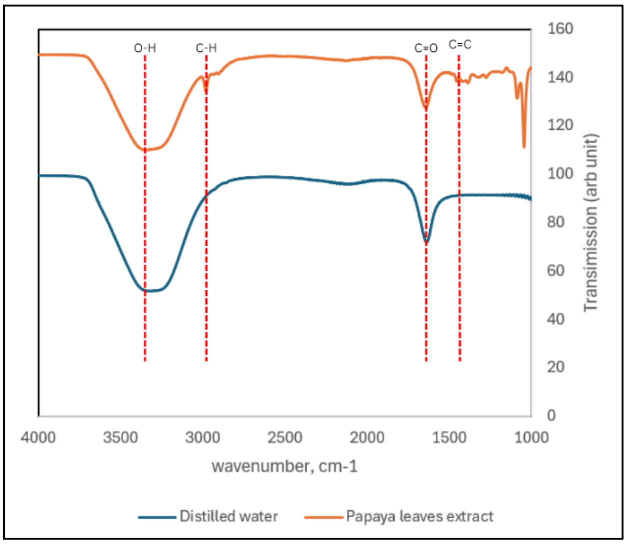

Fig. 5 FTIR plot for PLE and distilled water

3.2 Elemental Composition and Morphology Analysis using SEM-EDX

The SEM-EDX analysis demonstrates the effectiveness of PLE in reducing corrosion on copper surfaces exposed to NaCl solutions. The untreated sample, as illustrated in Fig. 6a, shows a smooth surface without visible signs of corrosion, serving as the baseline for comparison. In contrast, the 100% NaCl immersion sample, as presented in Fig. 6b, exhibits severe surface degradation, with noticeable corrosion pits and rough textures, confirming the aggressive nature of saline on unprotected copper. With the addition of 10% PLE to 90% NaCl, as depicted in Fig. 6c, the copper surface shows some improvement, with reduced corrosion compared to the untreated NaCl sample. However, surface damage remains visible, indicating limited protection at this concentration. Increasing the PLE concentration to 30% in 70% NaCl, as seen in Fig. 6d, provides better protection, as evidenced by fewer corrosion pits and a smoother surface texture. This improvement is attributed to the higher levels of bioactive compounds in the extract, enhancing its inhibitory effect.

The most effective results are observed with 50% PLE in 50% NaCl, as shown in Fig. 6e, where the copper surface exhibits minimal corrosion and a smooth, flat texture. This significant improvement is due to the formation of a protective layer by PLE on the copper surface, acting as a barrier to prevent further corrosion. A decrease in copper peaks and an increase in oxygen or carbon peaks indicated corrosion and the formation of protective layers by the inhibitor. Morphological observations, like smoother surfaces or fewer corrosion pits on treated samples, further demonstrated the effectiveness of the papaya leaf extract in preventing corrosion [9].

Table 1 Atomic percentage of Cu, O, Cl and Sn for various mixture of PLE inhibitor and NaCl solution

		Atomic %	Atomic %	Atomic %	Atomic %
Element	Raw Sample	100% NaCl	90% NaCl 10% Extract	70% NaCl 30 Extract	50% NaCl 50% Extract
Cu	98.2	47.8	49.8	55.7	84.0
O	0.0	26.2	22.3	25.0	10.8
Cl	0.0	1.1	1.1	1.0	0.2
Sn	1.8	24.9	26.8	18.3	5.0
Total	100	100	100	100	100

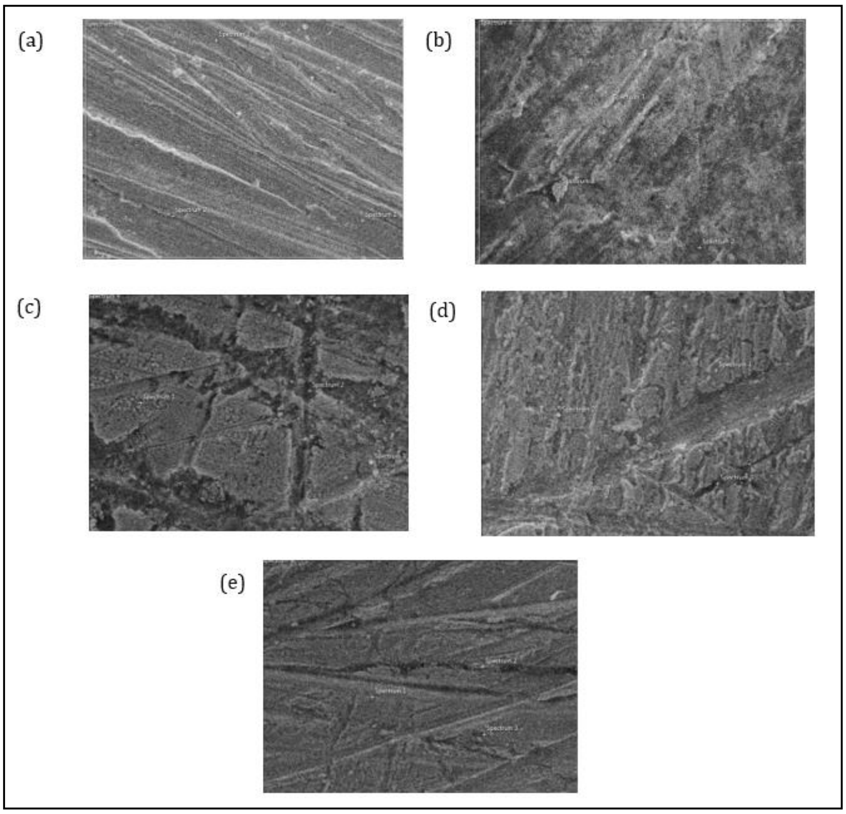

Fig. 6 The appearance of copper on PCB surface for (a) Raw sample, (b)100% NaCI immersion, (c) 90% NaCl 10% extract immersion, (d) 70% NaCI 30% extract immersion and (e) 50% NaCl 50% extract immersion

Table 1 shows the elemental composition of copper surfaces after different immersion conditions, analysed using SEM-EDX. In the raw sample, copper dominates at 98.2%, with no oxygen or chlorine detected, indicating a clean, uncorroded surface. Immersion in 100% NaCl significantly reduces the copper content to 47.8%, while oxygen rises to 26.2% and chlorine appears at 1.1%, showing severe corrosion. With 90% NaCl and 10% extract, copper slightly improves to 49.8% and oxygen decreases to 22.3%, suggesting partial protection. In 70% NaCl and 30% extract, copper rises to 55.7%, oxygen stabilizes at 25.0%, and chlorine reduces to 1.0%, reflecting better protection. Finally, in 50% NaCl and 50% extract, copper reaches 84.0%, oxygen drops to 10.8%, and chlorine is nearly eliminated at 0.2%, indicating the strongest corrosion inhibition.

The combination of 50% NaCl + 50% PLE (Plant Leaf Extract) is the most effective treatment for corrosion inhibition based on the data in the table and the figure. The atomic percentage table shows that this mixture retains the highest copper content at 84.0%, significantly higher than other treatments, indicating strong protection against copper dissolution. The oxygen content is the lowest at 10.8%, reflecting minimal oxidation and the formation of corrosion products. Chlorine, which accelerates pitting and corrosion, is nearly eliminated at 0.2%, and the tin content is reduced to 5.0%, suggesting less interaction with the corrosive environment and fewer secondary corrosion products. The chlorine comes from the NaCl solution used in the experiment. When copper is exposed to NaCl, chloride ions (Cl^-) promote pitting corrosion by breaking down the protective oxide layer on the metal surface.

The microscopic image Fig. 6e supports this claim, showing the smoothest and least damaged surface among all samples exposed to NaCl solutions. In contrast, the 100% NaCl sample (Figure b) exhibits severe surface degradation, while samples treated with lower PLE concentrations (10% or 30% extract) show intermediate levels of protection but still display more surface damage than the 50% extract. The 50% PLE concentration likely achieves optimal efficiency by forming a uniform protective barrier on the copper surface, attributed to its organic compounds, such as tannins, flavonoids, or polyphenols. These compounds adsorb onto the surface, reducing exposure to oxygen and chloride ions.

3.3 The Corrosion Rate of The Copper using EIS

The Tafel plot compares the electrochemical behaviour of copper in 100% NaCl and NaCl solutions with varying concentrations of papaya leaf extract (PLE) as a corrosion inhibitor. The graph shows how the addition of PLE reduces the corrosion current density, thereby mitigating the corrosion process. In the 100% NaCl solution, represented by the black curve, the plot exhibits steep anodic and cathodic branches with the highest current density, indicating aggressive corrosion due to the active dissolution of copper in the chloride environment. The absence of inhibition effects reflects pronounced electrochemical activity. With 90% NaCl and 10% PLE, represented by the red curve, the current density decreases, indicating partial inhibition. The reduction in both anodic and cathodic branches suggests that the PLE begins to form a protective layer on the copper surface, slowing down corrosion. For 70% NaCl and 30% PLE, shown by the green curve, a further reduction in current density is observed. This indicates stronger inhibition, as the higher concentration of PLE enhances the formation of a stable and effective protective layer, suppressing both anodic and cathodic reactions.

In the 50% NaCl and 50% PLE solution, represented by the blue curve, the more positive potential is achieved. This reflects the most effective corrosion inhibition, with a dense and uniform protective layer significantly reducing electrochemical activity. The nearly symmetrical decrease in both anodic and cathodic branches indicates that PLE acts as a mixed-type inhibitor, effectively suppressing both copper dissolution and oxygen reduction. Overall, the Tafel plot demonstrates that increasing the concentration of PLE enhances its ability to inhibit corrosion, highlighting its potential as an eco-friendly and effective corrosion inhibitor for copper in chloride environments.

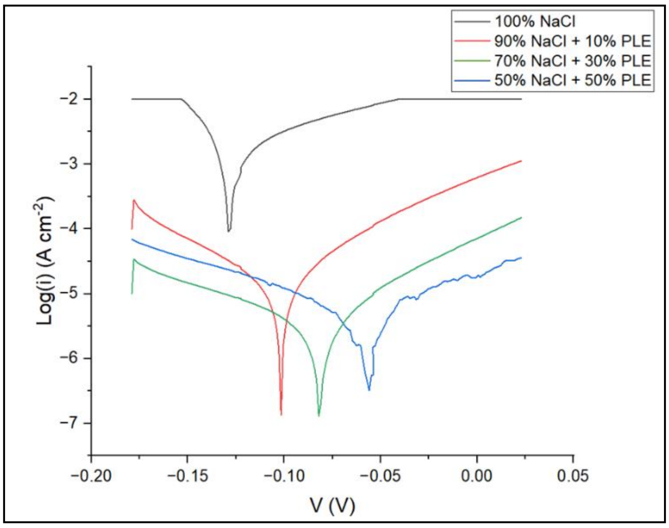

Fig. 7 Tafel plot comparison for copper in varying concentrations of PLE

The Nyquist plot compares the electrochemical impedance behaviour of copper in 100% NaCl and NaCl solutions with varying concentrations of papaya leaf extract (PLE) as corrosion inhibitors. The plot represents the relationship between the real impedance (Z′Z') and the imaginary impedance (−Z″-Z''). In the 100% NaCl solution, represented by the black line, the plot is small hemisphere curve, indicating a diffusion-controlled process typical of Warburg impedance. This behaviour reflects active corrosion with minimal charge transfer resistance R_{ct}, suggesting that electrochemical reactions, such as copper dissolution, occur freely without significant impedance.

For the solution with 90% NaCl and 10% PLE, represented by the red curve, a small semicircular arc begins to form, indicating the development of some capacitive behaviour and a slight increase in R_{ct}. This implies that a partial protective layer forms on the copper surface, slightly mitigating corrosion. The 70% NaCl and 30% PLE solution, represented by the green curve, shows a more prominent semicircular arc, reflecting a significant increase in R_{ct}. This indicates stronger corrosion inhibition as the higher concentration of PLE forms a more robust and stable protective layer.

In the 50% NaCl and 50% PLE solution, represented by the blue curve, the largest semicircular arc is observed, indicating the highest R_{ct}. This suggests the most effective corrosion inhibition, as the dense and uniform protective layer significantly impedes charge transfer and limits electrolyte penetration. The Nyquist plot confirms that increasing PLE concentration enhances corrosion resistance by shifting from diffusion-controlled behaviour in 100% NaCl to a system with higher resistivity. These results highlight PLE's effectiveness as a green corrosion inhibitor, demonstrating its ability to form a stable barrier that reduces metal degradation over time [10].

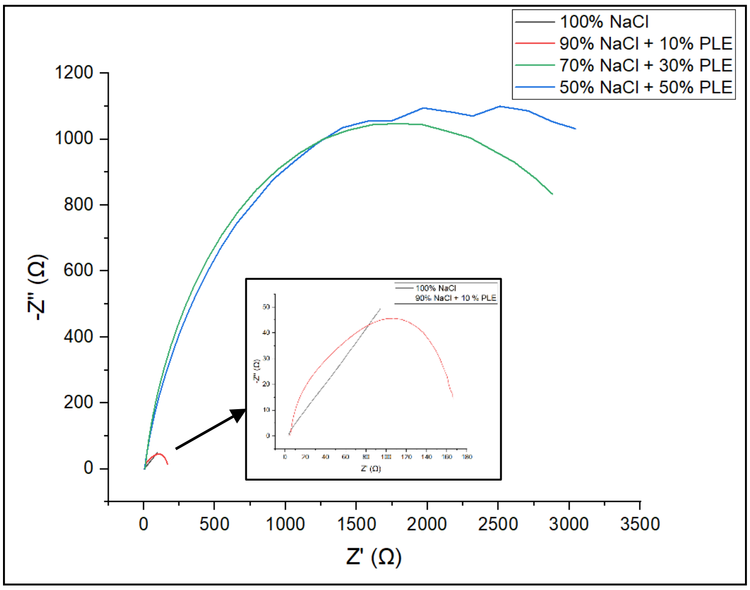

Fig. 8 Nyquist plot comparison for copper in NaCl with diverse concentrations of PLE

4. Conclusion

The FTIR analysis revealed the presence of O-H (~3400 cm^{-1}), C-H (~2900 cm^{-1}), C=O (~1700 cm^{-1}), and C=C aromatic vibrations (1600–1500 cm^{-1}), along with C-O or C-N stretching (~1200–1000 cm^{-1}), confirming the presence of bioactive compounds like polyphenols, flavonoids, and tannins, which play a crucial role in forming protective films on copper surfaces. SEM-EDX analysis showed that higher concentrations of PLE resulted in increased copper content (up to 84.0% for 50% PLE) and decreased oxygen content, indicating effective corrosion inhibition and the formation of a protective layer on the copper surface.

Electrochemical Impedance Spectroscopy (EIS) demonstrated that the charge transfer resistance increased significantly with higher PLE concentrations, as evidenced by larger Nyquist plot semicircles, highlighting the improved corrosion protection with a more stable and uniform inhibitor layer. The best corrosion inhibition performance was observed with 50% NaCl + 50% PLE, which provided the highest protection by forming a dense and uniform protective layer, significantly reducing both corrosion rate and surface degradation. This study supports the use of plant-based inhibitors as a sustainable alternative to hazardous chemical inhibitors, with potential applications in industries like electronics, marine, and infrastructure maintenance. Future research can focus on optimizing PLE extraction methods, testing long-term stability, comparing with other plant-based inhibitors, and assessing its effectiveness in real-world applications.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm their contributions to the paper as follows: ***study conception and design:*** *Nurmira Batrisyia Mohd Radzuan, Zaidi Embong, Siti Maisarah Rahim, Mohd Sidiq Mohd Basir;* ***data collection:*** *Nurmira Batrisyia Mohd Radzuan, Siti Maisarah Rahim, Mohd Sidiq Mohd Basir;* ***analysis and interpretation of results****: Nurmira Batrisyia Mohd Radzuan, Zaidi Embong;* ***draft manuscript preparation****: Nurmira Batrisyia Mohd Radzuan, Zaidi Embong. All authors reviewed the results and approved the final version of the manuscript.*

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