

Enhancement of Metal Electrode Corrosion Resistance through the Synergistic Effects of Three Organic Inhibitors: Jatropha Leaf, Tea Leaf, and Orange Peel Extracts

Salsabila Marcela, Romi Fadli Syahputra*, Delovita Ginting

Department of Physics, Universitas Muhammadiyah Riau, Pekanbaru, Indonesia, 28294

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Abstract

Corrosion of metal electrodes is a major challenge in energy storage systems due to its impact on performance and service life. This study investigates the synergistic effect of *Jatropha curcas* leaf extract, *Camellia sinensis* leaf extract, and *Citrus sinensis* peel extract on the corrosion resistance of zinc (Zn) electrodes. The active compounds were characterized using UV-Vis and FTIR spectroscopy, while functional groups were identified through deconvolution analysis. Corrosion performance was evaluated using immersion tests and Linear Sweep Voltammetry (LSV). Results showed the presence of hydroxyl and phenolic groups capable of forming a protective layer on the Zn surface. LSV analysis confirmed that the combined extracts exhibited a synergistic effect, significantly reducing the corrosion rate compared to individual extracts. These findings indicate that natural extract combinations have potential as environmentally friendly corrosion inhibitors for zinc-based energy storage applications.

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Abstrak

Korosi pada elektroda logam merupakan tantangan utama dalam sistem penyimpanan energi karena berdampak pada kinerja dan umur layanan. Penelitian ini mengkaji efek sinergis dari ekstrak daun *Jatropha curcas*, ekstrak daun *Camellia sinensis*, dan ekstrak kulit *Citrus sinensis* terhadap ketahanan korosi elektroda seng (Zn). Senyawa aktif dikarakterisasi menggunakan spektroskopi UV-Vis dan FTIR, sedangkan gugus fungsi diidentifikasi melalui analisis dekonvolusi. Kinerja korosi dievaluasi menggunakan uji perendaman dan Linear Sweep Voltammetry (LSV). Hasil menunjukkan adanya gugus hidroksil dan fenolik yang mampu membentuk lapisan pelindung pada permukaan Zn. Analisis LSV mengonfirmasi bahwa kombinasi ekstrak menghasilkan efek sinergis yang secara signifikan menurunkan laju korosi dibandingkan ekstrak tunggal. Temuan ini menunjukkan bahwa kombinasi ekstrak alami berpotensi sebagai inhibitor korosi ramah lingkungan untuk aplikasi penyimpanan energi berbasis seng.

1. Introduction

One of the main challenges in battery development is the corrosion of metal electrodes, which can reduce the lifespan and efficiency of energy storage systems. Electrode corrosion leads to performance degradation as well as potential damage due to undesirable chemical reactions (Ayub et al. 2022). Therefore, effective corrosion protection strategies are required to enhance the stability and performance of zinc-based materials.

With the growing emphasis on environmentally friendly materials, numerous studies have focused on the development of corrosion inhibitors derived from natural resources. Plant extracts have been recognized as promising green inhibitors due to their ability to protect metal surfaces against degradation caused by electrochemical reactions (Kong et al. 2023). The use of these natural materials not only provides a safer alternative to synthetic inhibitors but also promotes sustainability, as they are readily available and do not rely on imported chemical substances.

* Corresponding author.

E-mail address: romifadli@umri.ac.id

Consequently, the resulting corrosion protection technology is expected to be more economical and environmentally sustainable.

Furthermore, recent studies have focused on the development of organic-based corrosion inhibitors using a multi-component approach derived from local plant extracts. This strategy has demonstrated significant potential in enhancing corrosion protection efficiency through the synergistic interactions among active compounds (Hu et al. 2021). The utilization of abundant biological resources, particularly in Indonesia, also offers opportunities to strengthen self-reliance in the development of nature-based material technologies that are both simple and high-value.

Recent studies have highlighted the increasing interest in plant-derived organic corrosion inhibitors as environmentally friendly alternatives to conventional synthetic inhibitors because of their biodegradability, low toxicity, renewability, and cost-effectiveness (Salleh et al. 2021). Plant extracts are rich in phytochemical constituents, including flavonoids, tannins, alkaloids, saponins, and phenolic compounds, which can adsorb onto metal surfaces and form protective films that effectively suppress corrosion reactions (Salleh et al. 2021). Among the various natural inhibitors, *Camellia sinensis* (tea) leaf extract has demonstrated promising corrosion inhibition performance owing to its high polyphenol and catechin contents, while *Citrus sinensis* (orange) peel extract has also been reported as an effective green corrosion inhibitor due to the presence of flavonoids, limonene, and ascorbic acid that enhance corrosion resistance (Bandeira et al. 2025). In addition, numerous plant extracts have been successfully applied as corrosion inhibitors in acidic and saline environments, confirming the broad potential of phytochemical-based corrosion protection and encouraging the exploration of locally available biomass resources (Eddy et al. 2022). Nevertheless, most previous studies have focused on single-plant extract inhibitors, whereas investigations on the synergistic effects of combining multiple plant extracts remain limited (Zhang et al., 2025). Furthermore, the corrosion inhibition potential of *Jatropha curcas* leaves, particularly when combined with *Camellia sinensis* leaves and *Citrus sinensis* peels, has received little attention in recent studies. Therefore, this study investigates the synergistic combination of *Jatropha curcas* leaf extract, *Camellia sinensis* leaf extract, and *Citrus sinensis* peel extract as a multi-component organic corrosion inhibitor to develop a sustainable and more effective strategy for improving the corrosion resistance of zinc electrodes.

This study aims to improve the corrosion resistance of zinc electrodes by developing a multi-component organic inhibitor consisting of *Jatropha curcas* leaf extract, *Camellia sinensis* leaf extract, and *Citrus sinensis* peel extract. Unlike conventional studies that evaluate individual plant extracts separately, the three extracts were intentionally combined in predetermined compositions to exploit the complementary characteristics of their bioactive compounds. *Jatropha* leaf extract contributes tannins and phenolic compounds that promote strong adsorption on the metal surface, tea leaf extract provides abundant catechins and polyphenols that enhance the formation of protective films, while orange peel extract supplies flavonoids, limonene, and ascorbic acid that improve surface coverage and corrosion resistance. The combination of these extracts is expected to produce synergistic interactions that result in a more stable and compact protective layer than single-component inhibitors. Therefore, the proposed multi-component inhibitor offers a sustainable and environmentally friendly strategy for improving the corrosion resistance of zinc electrodes.

2. Research Methods

The materials used in this study included orange peel waste (*Citrus sinensis*), tea leaves (*Camellia sinensis*), castor leaves (*Jatropha curcas*), 1 M sodium chloride (NaCl) solution, sodium benzoate, and distilled water. The equipment used in this study consisted of an analytical balance, measuring cylinder, dropper pipette, stirring rod, and mixer.

2.1 Zinc Electrode Preparation

Zinc (Zn) was used as the electrode material in this study. The electrode specimens were prepared with dimensions of 7 × 2 cm. Part of the electrode surface was coated with epoxy, leaving an exposed area of 2 cm for corrosion testing. The exposed surface was polished with sandpaper to obtain a smooth finish, rinsed with demineralized water, dried, and weighed to determine the initial mass before immersion.

2.2 Preparation of *Jatropha curcas* Leaf, *Camellia sinensis* Leaf, and *Citrus sinensis* Peel Extracts

The collected *Citrus sinensis* peel waste, *Jatropha curcas* leaves, and *Camellia sinensis* leaves were first washed thoroughly under running water to remove dust and impurities. The materials were then dried under direct sunlight for 1–2 hours to reduce their moisture content. This drying process was intended to prevent microbial growth and facilitate the grinding process. The dried materials were subsequently ground into fine powder using a mixer. The powders obtained from the orange peels, castor leaves, and tea leaves were weighed and stored in closed containers. The extraction process was carried out using the maceration method, in which the powdered materials were immersed in distilled water at a solid-to-solvent ratio of 1:10 (w/v). Maceration was performed for 72 hours at room temperature with occasional stirring to enhance the diffusion of active compounds into the solvent.

Table 1. Formulation of multi-component organic inhibitors used in this study

Sample Code	<i>Jatropha curcas</i> leaf extract (ml)	<i>Citrus sinensis</i> peel extract (ml)	<i>Camellia sinensis</i> leaf extract (ml)	Distilled Water (ml)	Total Volume (ml)
Control	0	0	0	25	25
DJT 1	10	5	5	25	45
DJT 2	5	10	5	25	45
DJT 3	5	5	10	25	45
DJT 4	15	5	5	25	50
DJT 5	5	15	5	25	50
DJT 6	5	5	15	25	50

Note: DJT1–DJT6 represent six formulations of a multi-component organic inhibitor. Each formulation contains the same three plant extracts, while the volume of the dominant extract was varied to evaluate the effect of composition on corrosion inhibition performance.

2.2.1 Corrosion Rate Measurement Using the Linear Sweep Voltammetry (LSV) Method

Linear Sweep Voltammetry (LSV) is an electrochemical technique widely used to evaluate the corrosion rate of metals by measuring the current response while the electrode potential is scanned linearly using a potentiostat. LSV measurements were conducted using a three-electrode system consisting of a zinc (Zn) working electrode, an Ag/AgCl reference electrode, and a graphite pencil counter electrode. This technique enables the identification of corrosion behavior and oxidation reactions with high accuracy. The validity and reproducibility of the obtained data strongly depend on the electrode configuration, particularly the selection of electrode types and the distance between the electrodes (Mimoun et al. 2023).

The linear sweep voltammetry (LSV) measurements were performed at a scan rate of 1 mV s⁻¹, which was selected based on previous studies demonstrating that this scan rate provides stable polarization curves and enables reliable determination of corrosion parameters through Tafel extrapolation (Krawiec et al. 2024, Zhou et al. 2024). The potential window was adjusted according to the characteristics of the zinc electrode and the electrolyte used. Variations in the potential range may influence the shape of the LSV curves as well as the estimation of the corrosion potential (E_{corr}) and corrosion current density (I_{corr}). The I_{corr} value was determined using the Tafel extrapolation method from the LSV curves and was subsequently used to calculate the corrosion rate (CR) according to the following equation:

$$CR = \frac{K \cdot I_{corr} \cdot EW}{n \cdot \rho} \quad (1)$$

where K is the conversion constant, EW is the equivalent weight, n is the number of electrons involved in the reaction, and ρ is the density of the metal. This approach is commonly applied in corrosion studies involving battery electrodes and stainless steel materials.

2.3 Evaluation of Corrosion Inhibition Performance

The electrode material used in this study was zinc (Zn) metal in the form of a standard sheet. The Zn sheet was cut into eight specimens measuring 7 × 2 cm using metal shears, corresponding to the number of inhibitor formulation variations to be tested. The preparation of electrodes with uniform dimensions was intended to ensure consistency and reliability of the experimental results (Gupta et al. 2023). After cutting, the Zn electrode surfaces were polished using progressively finer grades of sandpaper to remove oxide layers and other surface impurities, resulting in a clean and homogeneous surface. This surface treatment was performed to ensure uniform initial surface conditions among all electrode specimens prior to corrosion testing (Kumar et al. 2022).

Subsequently, the polished Zn electrodes were coated with epoxy resin over the central portion, leaving 2 cm exposed at the upper end and 1 cm at the lower end. The exposed sections served as the electrical contact area for electrochemical measurements and as the region immersed in the inhibitor solution. The epoxy-coated electrodes were then dried at room temperature until the coating was completely cured and firmly adhered to the electrode surface (Muresan et al. 2021). To verify the quality of the coating, the dried electrodes were tested using a digital multimeter to confirm that the epoxy-covered surface was electrically insulated, thereby preventing interference during corrosion measurements. Consequently, only the exposed electrode area was allowed to interact directly with the inhibitor solution throughout the electrochemical tests.

3. Results and Discussion

3.1 UV-Vis Spectroscopy Analysis

Two major absorption peaks with high intensity were observed at approximately $\lambda \approx 250$ –300 nm and $\lambda \approx 350$ –400 nm, indicating the presence of chromophore groups such as aromatic C=C bonds, C=O groups, and conjugated double bonds. The gradual absorption tail observed beyond 400 nm suggests the presence of extended conjugated

systems within the organic compounds. Furthermore, differences in the spectral profiles among the samples indicate variations in the concentration of active compounds. Samples exhibiting higher absorption intensities are likely to contain greater amounts of light-absorbing compounds, such as polyphenols and alkaloids, which may contribute to enhanced corrosion inhibition performance.

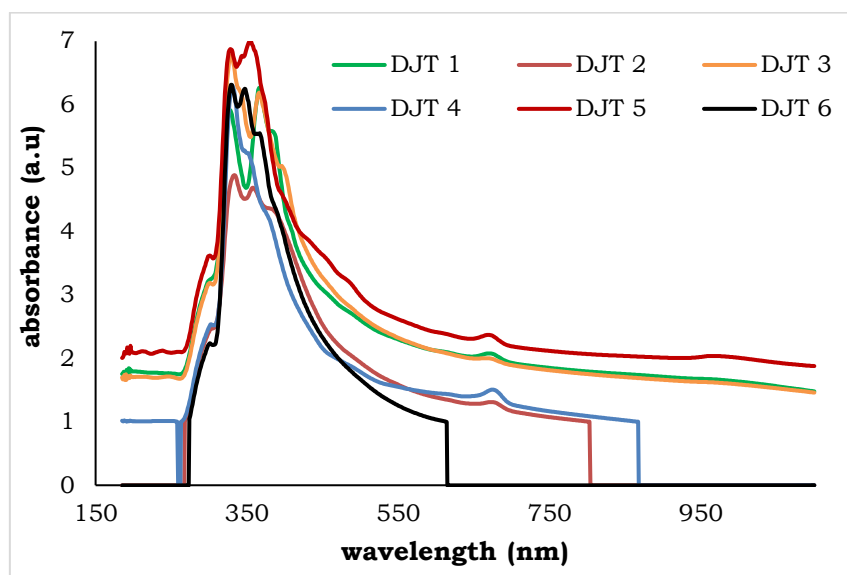


Figure 1. UV-Vis Spectra of the DJT Sample Variations (DJT 1–DJT 6)

3.2 FTIR Spectrum Analysis

The deconvolution analysis of the FTIR spectra for both single extracts and combined formulations (DJ, DT, JT, KD, and KJ) revealed dominant absorption bands in the range of $3200\text{--}3400\text{ cm}^{-1}$, which are generally attributed to O–H (hydroxyl) and N–H (amine) stretching vibrations. These functional groups play an important role in the adsorption process of corrosion inhibitors onto the metal surface, as they are capable of donating lone-pair electrons and forming a protective layer against corrosive ions (Yang et al. 2021).

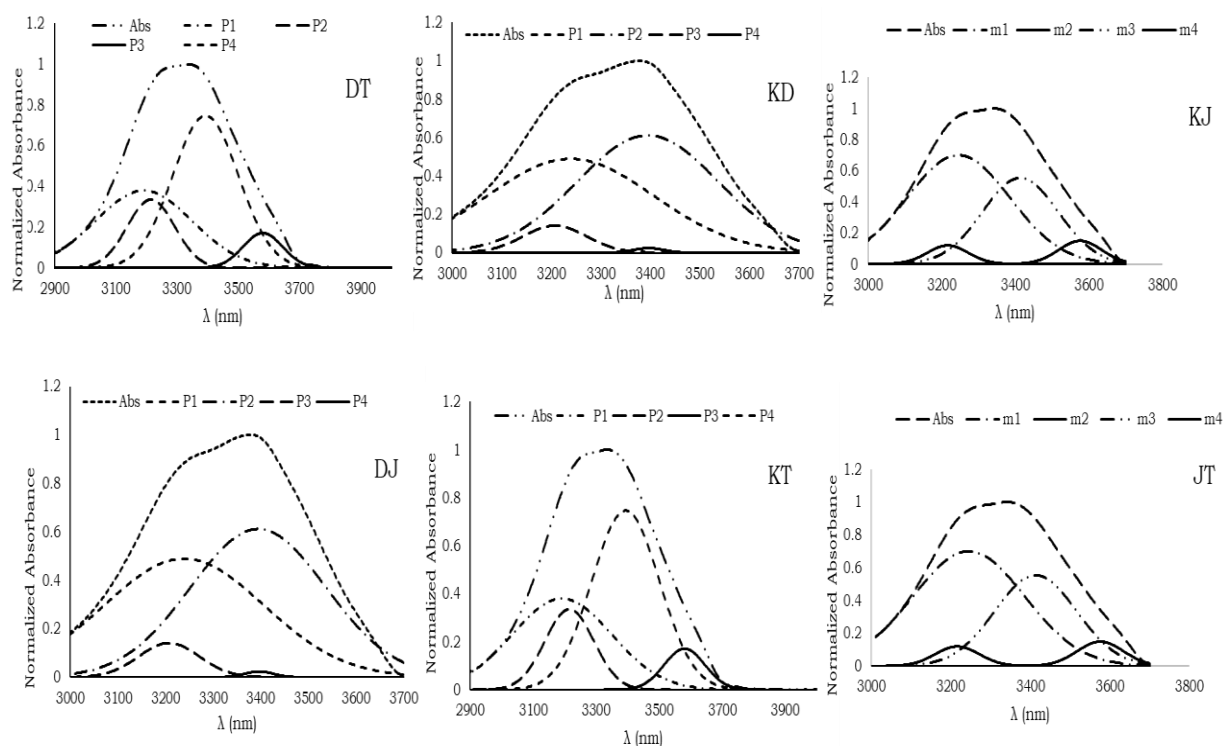


Figure 2. FTIR spectral deconvolution analysis of the inhibitor extract samples

In the *Jatropha curcas* leaf extract (DJ), a strong absorption band at 3394 cm^{-1} with high intensity and a narrow full width at half maximum (FWHM) indicates the presence of relatively pure and stable hydroxyl groups. This finding

is consistent with the presence of polyphenolic compounds, which can interact with the metal surface through coordination bonding. Meanwhile, the *Camellia sinensis* leaf extract (DT) exhibits a distinctive feature with the appearance of an absorption band at 3580 cm^{-1} , indicating the presence of free hydroxyl ($-\text{OH}$) groups that are not involved in hydrogen bonding. Such functional groups are characteristic of catechins and tannins, the major compounds found in tea, which are known to contribute significantly to corrosion inhibition performance (Rafik et al. 2022)

Table 2. Parameters of the mixed organic inhibitor formulations

Sample	Parameter	P1	P2	P3	P4	P5
DJ	Peak position (cm^{-1})	3207.2	3238.8	3394.5	3396.4	-
	Peak height (a.u.)	22.64	205.92	218.06	1.796	-
	FWHM (cm^{-1})	0.1412	0.4891	0.6113	0.0239	-
DT	Peak position (cm^{-1})	3191.1	3214.7	3393.2	-	3580.0
	Peak height (a.u.)	150.72	65.36	201.09	-	27.86
	FWHM (cm^{-1})	0.3800	0.3353	0.7467	-	0.1712
KD	Peak position (cm^{-1})	3161.7	3258.9	-	3422.5	3565.5
	Peak height (a.u.)	93.50	220.47	-	94.54	45.56
	FWHM (cm^{-1})	0.1662	0.7642	-	0.4815	0.2599
JD	Peak position (cm^{-1})	3207.5	3321.7	3357.0	-	-
	Peak height (a.u.)	4.00	476.71	13.016	-	-
	FWHM (cm^{-1})	0.0269	0.3656	0.0517	-	-
JT	Peak position (cm^{-1})	3216.1	3245.1	-	3413.2	3575.8
	Peak height (a.u.)	16.59	246.53	-	142.61	21.80
	FWHM (cm^{-1})	0.1189	0.6970	-	0.5530	0.1485

The combination of *Jatropha curcas* and *Camellia sinensis* extracts (JT) exhibited a broader absorption band with an FWHM value of up to 0.76, indicating interactions between phenolic functional groups that may generate a synergistic effect. The increased band width suggests the involvement of multiple functional groups in hydrogen bonding and adsorption processes, resulting in the formation of a more heterogeneous yet stable protective layer. This finding is consistent with previous studies reporting that combinations of organic inhibitors tend to enhance corrosion inhibition efficiency through synergistic mechanisms (Zhang et al. 2021).

The KD sample exhibited a very high-intensity absorption band (476) at 3321 cm^{-1} with a very narrow FWHM, indicating the predominance of a specific type of chemical bond. Although this absorption band was remarkably strong, the limited diversity of functional groups may reduce its long-term protective effectiveness due to the lack of multiple adsorption mechanisms. In contrast, the KJ sample displayed a broad absorption band with relatively high intensity (246 at 3245 cm^{-1}), consistent with the presence of flavonoids and limonene compounds. These compounds are known to interact with metal ions through aromatic systems and hydroxyl functional groups, thereby enhancing corrosion protection performance (Muresan et al. 2021).

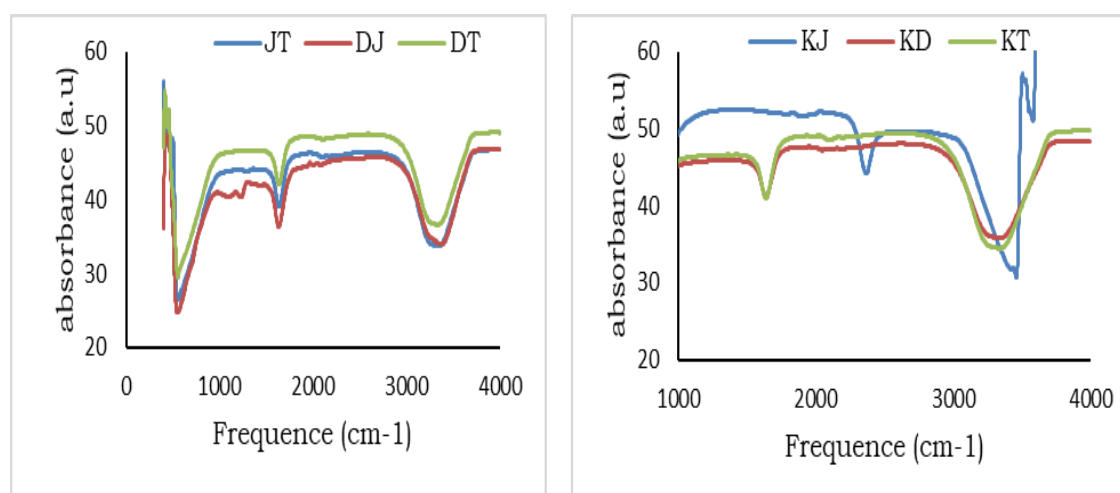


Figure 3. FTIR Spectrum Analysis

3.3 Linier Sweep Voltametry (LSV) Analysis

The Linear Sweep Voltammetry (LSV) measurements revealed that the addition of the organic inhibitor formulations influenced the electrochemical corrosion behavior of zinc electrodes. Variations in the inhibitor composition produced different polarization responses, resulting in changes in corrosion potential (E_{corr}), corrosion current density (I_{corr}), corrosion rate (CR), and inhibition efficiency (IE). The Tafel polarization curves obtained from

the LSV measurements are presented in Figure 4, while the corresponding corrosion parameters are summarized in Table 3.

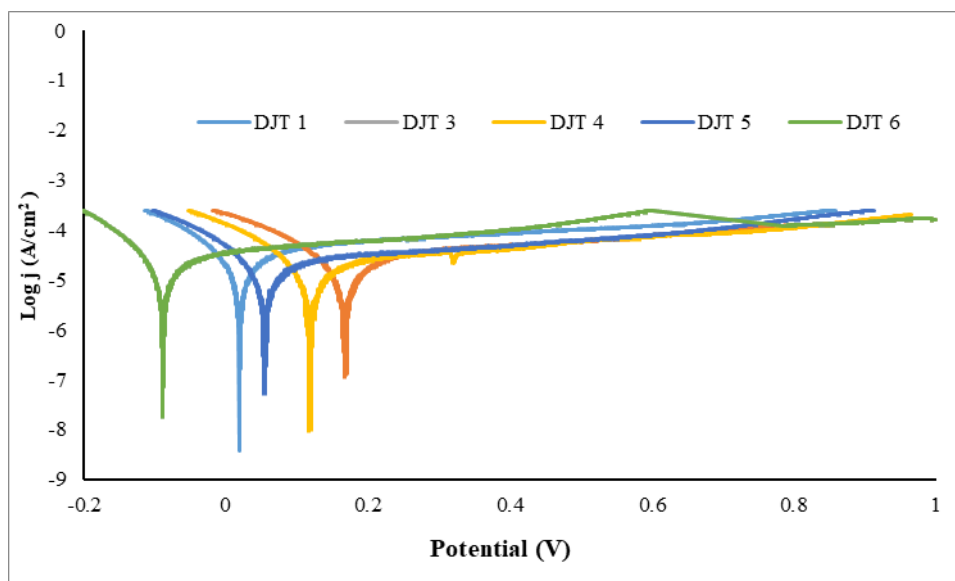


Figure 4. Tafel Curves of DJT Sample Variations (DJT 1–DJT 6)

Table 3. Corrosion parameters obtained from LSV measurements

Sampel	Corrosion rate, CR (mm/y)	i_{corr} ($\mu\text{A}/\text{cm}^2$)	IE (%)
control	0.1287	34.38	-
DJT 1	0.1521	40.63	-18.19
DJT 2	0.1202	32.12	6.61
DJT 3	0.0975	26.04	24.24
DJT 4	0.1755	48.96	-36.36
DJT 5	0.1038	27.79	19.35
DJT 6	0.0981	26.21	23.78

Based on the Tafel polarization curves (Figure 4) and the corrosion parameters presented in Table 3, the DJT6 formulation exhibited a noticeable leftward shift compared with the other formulations, indicating a lower corrosion tendency and effective corrosion inhibition performance. This behavior can be attributed to the synergistic interaction among *Jatropha curcas* leaf extract, *Camellia sinensis* leaf extract, and *Citrus sinensis* peel extract. The higher proportion of *Camellia sinensis* leaf extract in the DJT6 formulation provides abundant polyphenols, flavonoids, and tannins, which readily adsorb onto the zinc surface and form a protective film that suppresses both anodic and cathodic corrosion reactions. As presented in Table 3, the corrosion rate values obtained from the LSV measurements ranged from 0.0975 to 0.1755 mpy, indicating that the inhibitor formulations exhibited different levels of corrosion protection depending on their composition. These results are comparable to previous studies on plant-based corrosion inhibitors. Indarti (2022) reported that green tea extract reduced the corrosion rate of brass from 3.95 mm y⁻¹ to 0.23 mm y⁻¹ in a 3.56% NaCl solution, while demonstrated that coatings derived from tea waste and orange peel extract decreased the corrosion rate of mild steel from 3.4523 mm y⁻¹ to 0.0377 mm y⁻¹ and 0.0455 mm y⁻¹, respectively. Although direct comparison of corrosion rate values should be interpreted with caution because of differences in substrate materials, corrosive media, inhibitor formulations, and experimental conditions, these findings consistently demonstrate that plant-based organic inhibitors effectively reduce corrosion through the adsorption of phytochemical compounds, resulting in the formation of a stable protective layer on the metal surface.

4. Conclusions

Based on the results of this study, it can be concluded that *Jatropha curcas* leaf extract, *Camellia sinensis* leaf extract, and *Citrus sinensis* peel extract have demonstrated potential as organic corrosion inhibitors for improving the corrosion resistance of zinc (Zn) electrodes. Characterization results revealed the presence of active functional groups, such as hydroxyl (–OH) groups, polyphenols, and chromophoric compounds, which play important roles in the adsorption mechanism on the metal surface. Electrochemical testing indicated a significant reduction in the corrosion rate, while the combination of the three extracts exhibited a synergistic effect that provided better corrosion protection than the individual extracts.

Although this study successfully demonstrated the effectiveness of organic inhibitors in mitigating the corrosion process, several limitations were identified, including the limited variation of inhibitor concentrations, the absence of detailed surface analysis, and the restricted testing duration, which may have affected the achievement of the expected outcomes. Nevertheless, the primary objective of this research was achieved, demonstrating that the utilization of locally available plant extracts represents an environmentally friendly and sustainable alternative for metal corrosion control.

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