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Evaluation of Titanium (IV) Oxide Nano Powder-Hunteria umbellata Seed Extract Composite Coating on Mild Steel Immersed in Acidic Media for Corrosion Inhibition

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A B S T R A C T

The problem of wear and corrosion of materials has been a major industrial concern that needs to be addressed and mitigated. The search for eco-friendly, cheap, and toxic-free green materials that are durable and corrosion-resistant has remained a focus of research to protect infrastructures from failures. Green composite materials can be an alternative to synthetic inorganic inhibitor materials. This work examines the properties of titanium (IV) oxide - Hunteria umbellata seed extract composite on mild steel in acidic solutions of 5% HCl and 5% H2SO4. Characterization of material samples was done using X-ray diffraction (XRD), Scanning Electron Microscopy (SEM), and Fourier transform spectroscopy (FTIR). Corrosion rates, surface coverage, and inhibition efficiency were evaluated. The inhibition efficiency of the mild steel coated with composite was observed to have higher efficiency (76.9%) in HCI and offer higher resistance compared to H2SO4 (74.0%). The composite coating on the mild steel surface serves as a barrier and protective layer to corrosion.

1. INTRODUCTION

Wear damage and poor corrosion resistance in metals have constituted a threat to infrastructure, leading to material failure, disaster, loss of lives, substantial economic loss, and safety concerns [1-6]. Protection of infrastructure, industrial accessories, and storage devices against wear and corrosion remains can be done by using a corrosion inhibitor or applying a covering layer [7]. The challenge raised or posed by poor resistance of metals to corrosion remains a nightmare to be fully solved by synthetic organic inhibitors in the 21st century. The common synthetic organic inhibitors found on the market are toxic, expensive, non-environmentally friendly, non-biodegradable, and the by-products contaminate the environment coupled with health hazards [8]. Hence, the need arises to source cost-effective, economical, environmentally friendly, compatible, and sustainable green materials that can be harnessed from active parts of plant extracts as an alternative for corrosion inhibition [9-15]. Plant active components or parts have been explored, investigated, and utilized to inhibit corrosion in mild steels such as Sim's peel [16], moringa oleifera [17], Biebersteinia multifida [18], Aloe vera [19,20], Longan seed and peel [21], Rice husk [22,23], Garcinia indica [24], Mahonia nepalensis [25], olive leaf [26], Pisum sativum [27], Azadirachta indica [28], Ipomoea batatas [29], Apricot pomace [30], Gardenia jasminoides fruit [31], and Pomelo peel [32]. The search for green materials as an alternative to synthetic organic coatings to inhibit corrosion cannot be exhausted. Metal oxide titanium (IV) oxide or titanium dioxide has received recognition as a corrosion inhibitor due to its unique properties such as chemical stability in adverse weather, high optical properties, wide band gap, non-toxicity, and low cost. Titanium dioxide can exist in an amorphous state and crystalline phases and has shown promise in providing adequate corrosion protection [33,34]. Titanium dioxide is widely used as an anti-reflection coating, white pigment, biomaterial, and additive in composite coatings to enhance corrosion resistance [34-38]. Mild steel is an iron-alloyed metal used in industrial aqueous systems and metal-related product infrastructures. Hydrochloric and sulfuric acid quickens corrosion rates in infrastructure and industries, especially in the gas and oil sectors [39]. Hunteria umbellata is a tropical rainforest tree readily found in Nigeria and many parts of West and Central Africa. It is acknowledged as a constituent in herbal remedies for treating fever, abdominal discomforts, piles, infertility, and diabetes. Hunteria umbellata plant extract is eco-friendly and non-toxic and is known to exhibit corrosion inhibition properties based on its bioactive constituents [40]. Alaneme et al., [22] experimented with Hunteria umbellata extract on mild steel in acidic media for corrosion inhibition, the outcome of their studies showed the efficiency of inhibition properties of Hunteria umbellata increased as extract concentration was increased but an increase in temperature caused a decrease in inhibition efficiency. A report on the use of TiO2- Hunteria umbellata composite for coating mild steel is very rare in the literature. In a related study, Li et al., [41] investigated the influence of different TiO_2 nanoparticle concentrations on epoxy-based composite coatings' structural and mechanical properties. Their study highlighted the enhanced hardness and corrosion resistance attributed to the uniform dispersion of TiO_2-NPs within the coating matrix. Garcia et al., [42] explored the antimicrobial properties of TiO_2-NPs embedded in coatings. The research emphasized the potential dual functionality of TiO_2-NPs, acting not only as corrosion inhibitors but also as a barrier to microbial colonization on coated surfaces. Patel et al., [43] investigated the synergistic effects of TiO_2-NPs and plant extracts in polymer coatings. The outcome of their research demonstrated improved corrosion resistance and anti-fouling properties, underscoring the potential of combining metal oxide with natural plant extract as a composite for enhanced coating performance. This study examines the corrosion resistance behavior of titanium dioxide- Hunteria umbellata seed extract composite applied on the surface of mild steel in acidic media of 5% hydrochloric acid (HCI) and sulfuric acid (H_2SO_4) and the result presented.

2. EXPERIMENTAL PROCEDURES

2.1 Materials

The mild steel rod used has an elemental composition given in Table 1. Titanium (IV) oxide nano powder < 35 nm and 97% purity (Sigma Aldrich, USA), deionized-H_2O, HCl, and H_2SO_4 were used as obtained. Hunteria umbellata Pods, the green material to serves as a component of composite for corrosion inhibition were obtained from a nearby state in Nigeria which is readily available. The seeds were extracted, dried, and crushed into nanoparticles for use.

Table1. EDX elemental composition of mild steel.

Element	C	O	Fe	CI	Cu	Si	Ca	Mg	Na	Zn
Wt. %	3.20	10.30	16.20	2.02	2.17	0.50	1.60	4.25	2.10	6.25

2.2 Preparation of mild steel samples

For the experimental study, the mild steel was cut into sizes of dimension 0.14 cm x 3 cm and surfaces were polished using silicon carbide paper. Each coupon or sample was cleaned with ethanol, rinsed with acetone, and isopropanol alcohol, and dried in a stream of nitrogen gas. These samples prepared were and kept in a moisture-free desiccator.

2.3 Preparation of Hunteria umbellata seed extracts

Hunteria umbellata pods obtained were washed with water and deionized water to remove organic and inorganic impurities. The seeds were extracted from the pods and ambient temperature dried for 21 days pulverized and sieved. The sieved fine nanoparticles were kept for composite synthesis.

2.4 Synthesis of Titanium (lV) oxide- Hunteria umbellata seed extract nanocomposite

15.0 g of pulverized nano-size Hunteria umbellata seed extract was weighed and dissolved with a known quantity of Titanium (IV) oxide nanopowder in 30ml of ethanol in a beaker. The solution was stirred using a magnetic stirrer for a homogeneous mixture without heat for 4 hrs. A slurry or pasty nanocomposite solution was obtained. The prepared mild steel samples were immersed in slurry nanocomposite solution by dip-coating method for uniform surface coverage of mild steel. The coated mild steel samples were then sintered in an oven (Syspro lab instruments: model 9023A) for 45 minutes at 100 ºC for corrosion studies.

2.5 Analytical measurement of weight loss

The coated and uncoated mild steel samples were weighed and recorded before immersion in 100 ml capacity beakers containing 5% acidic solutions of HCl and H_2SO_4 respectively for 60 days as a function of time. Each sample immersed was reweighed at intervals of 10 days by retrieving the sample from the solution, rinsed with acetone, dried properly, and reweighed. The difference in weight was noted and recorded as weight loss. Corrosion rate (CR) was calculated using the ASTM G31[44] standard formula in equation (1).

$$CR_{(mm/y)} = \frac{87{,}500 \text{ x w}}{\text{A x } \rho \text{ x t}} \quad (1)$$

Where CR is the corrosion rate, W is the weight loss (g), A is the area of the coupon in cm^2 (20.72 cm^2 = exposed surface area for the mild steel), and t is time, **ρ** is the density (7.85g/cm^3 for the mild steel). The surface area (θ) from the corrosion rate is a result of the adsorption of inhibitor molecules. The surface coverage (θ) was calculated by using equation (2):

$$\theta = \frac{CR_{blank} - CR_{inhibitor}}{CR_{blank}} \quad (2)$$

The inhibition efficiency (I.E ɳ%) was determined using equations (2) and (3).

$$IE\ \% = \frac{CR_{blank} - CR_{inhibitor}}{CR_{blank}} \text{ x } 100 \quad (3)$$

Where CR $_{inhibitor}$ is the corrosion rate in the presence of inhibitor (composite), whereas CR $_{blank}$ is the corrosion rate in the absence of inhibitor (composite).

3. RESULTS AND DISCUSSION

3.1 Analytical weight Loss data and calculation

Table 2 summarizes the weight loss in both acidic solutions for the coated and uncoated mild steel for 60 days duration as a function of time. The weight loss is attributed to a corrosion attack on the surface of mild steel as a result acidic solution. Table 3 shows the calculated values of weight loss and mass loss. Using the weight loss for both acidic solutions. Table 4 depicts the corrosion rate (CR), surface coverage (Θ), and inhibition efficiency (ɳ %) calculated for both coated and uncoated mild steel in 5% HCl and H_2S0_4 solution respectively. The samples coated with composite offered high resistance to corrosion and performed better than the uncoated samples in both acidic solutions. Mild steel coated with composite performed better and more effectively in HCl compared to H_2S0_4 solution with inhibition efficiency of 76.9% and 74% respectively, an improvement on the previously reported study [22,23]. It was noted that weight loss and mass loss in coated mild steel samples are lower than that of uncoated samples in acidic media. The application of composite on the mild steel formed a protective barrier layer that hindered the access of corrosive agents (HCI and H_2S0_4). The composite acted as an adsorption mechanism by forming a hydrophobic layer around the mild steel.

Table 2. Variation of weight loss versus time (in days).

Intervals (days)	Specimen A: Coated mild steel (g), immersed in HCl solution	Specimen B: Uncoated mild steel (g), immersed in HCl solution	Specimen C: Coated mild steel (g), immersed in H_2SO_4 solution	Specimen D: Uncoated mild steel (g), immersed in H_2SO_4 solution
0	27.00	23.50	27.00	24.50
10	27.00	21.65	27.90	22.45
20	28.50	20.00	27.10	20.00
30	29.55	19.50	30.50	18.50
40	30.10	18.75	28.50	16.80
50	28.70	17.50	26.10	15.50
60	25.50	17.00	24.30	14.10

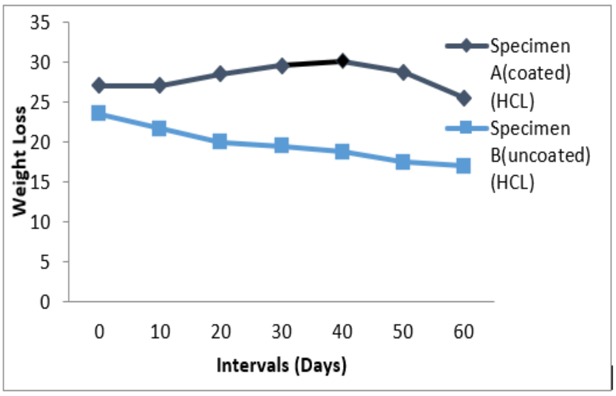
Table 3. The weight loss and mass loss data for the coated and uncoated mild steel.

Specimen identification	Acid solution	Initial weight (g)	Final weight (g)	Weight loss (g)	Exposure time (days)	Mass loss (g/cm²)
Specimen A: Coated with composite	HCI	27.00	25.50	1.50	60	0.0724
Specimen B: Uncoated with composite	HCI	23.50	17.00	6.50	60	0.3137
Specimen C: Coated with composite	H_2SO_4	27.00	24.30	2.70	60	0.1303
Specimen D: Uncoated with composite	H_2SO_4	24.50	14.10	10.40	60	0519

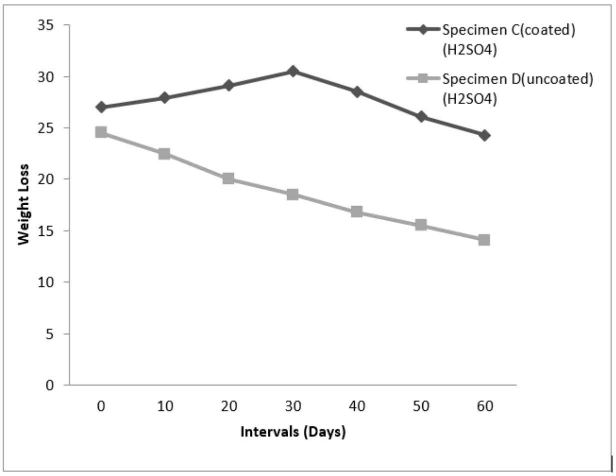
Table 4. Presents the tabulated corrosion rate, surface coverage, and inhibition efficiency (η %) for the coated and uncoated mild steel sample in 5% HCl and H_2S0_4, respectively.

Specimen	CR (mm/y)	Surface coverage (θ)	Inhibition efficiency (η%)
Specimen A	0.00056	0.769	76.9
Specimen B	0.00243		
Specimen C	0.00101	0.740	74.0
Specimen D	0.00389		

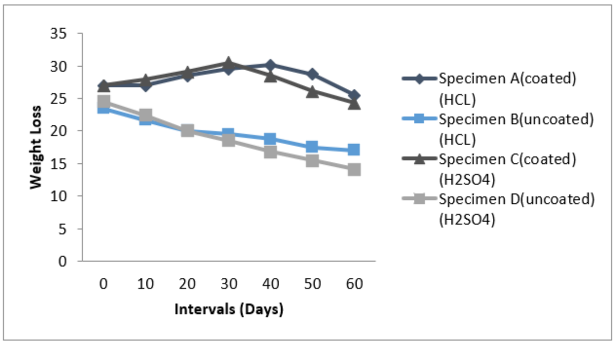
Figure 1 (a, b, and c) shows the plot of weight loss versus time (in days) for the coated and uncoated samples in 5% HCL and H_2SO_4 solutions. Figure 1a shows the graph of weight loss versus time (in days) for coated and uncoated samples in HCI solution. Figure 1b depicts a graph of weight loss versus time (in days) for coated and uncoated samples in H_2SO_4 solution. Figure 1c is the combined plotted graph of weight loss versus time (in days) for the acidic solutions. It was observed that the coated mild steel weight loss and mass loss are lower compared to uncoated in acidic solutions. It was also, observed that the weight loss and mass loss in HCI are lower compared to the H_2SO_4 solution.



(a) Graph of weight loss versus time for coated and uncoated mild steel in HCl



(b) Graph of weight loss versus time for coated and uncoated mild steel in H_2SO_4



(c) Graph of weight loss versus time for coated and uncoated mild steel in HCl and H_2SO_4

Fig. 1. (a, b and c): Graph plot of weight loss versus time of coated and uncoated mild steel both in 5% HCI and H_2SO_4.

3.2 FTIR spectroscopic analysis

Analysis of FTIR spectra of the Hunteria Umbellata seed extract is shown in Figure 2 and tabulated in Table 5. The characterization of the seed extract was done using a spectrophotometer model (ASCII PEDS 1.60). The various functional groups, compounds, and bonds present in the extract were identified in accordance with data by [45,46]. Hunteria umbellata seed extract constituents contributed uniquely to corrosion inhibition through the adsorption process. Hunteria umbellata seed extract showed the presence of hydrogen and oxygen atoms responsible for functional groups (OH, O-H, N-H, C-H, C=C, etc.). Figure 3. shows the spectroscopic FTIR graph of titanium (IV) oxide nanopowder used to synthesize as a composite. Table 6 depicts various functional groups, chemical constituents, and bonds embedded in titanium (IV) oxide nanopowder.

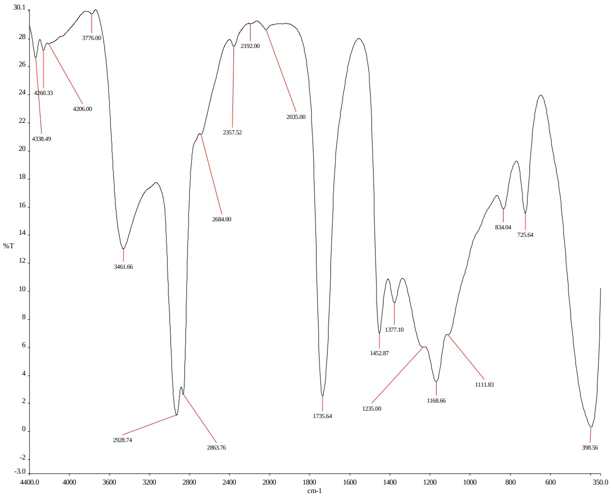


Fig. 2. FTIR spectrum of Hunteria Umbellata seed extract.

Table 5. Tabulated analysis of FTIR Spectrum of Hunteria umbellata seed extract.

Functional group/compound	**Absorption Peaks Wavenumber (cm^{-1})**	**Type of bond**
O-H stretch	4338.49	single
O-H stretch	4206.00	single
O-H stretch	3776.00	single
Hydroxyl, H-bonded, O-H stretch	3461.66	single
Methylene, C-H Asymmetric/symmetric stretch	2928.74, 2863.26	single
NH component	22357.52, 2035.00	Triple
Aldehyde, carbonyl compound.	1735.64	Double
Methylene, C-H bend	1452.87	Single
Trimethyl (Multiplet)	1377.10	single
Aromatic ethers aryl-O stretch	1235.00	single
Secondary amine, C-N stretch	1168.66	single
Aliphatic fluoro compound C-F stretch	1111.83	single
Skeletal C-C vibration	834.04	single
Skeletal C-C vibration, methylene–$(CH_2)_n$- rocking	725.64	single
Fingerprint	398.56	single

Figure 4 shows the FTIR spectroscopy graph of the Titanium (IV) oxide- hunteria umbellata composite there are more absorption band peaks at the lower wavenumber of the composite compared to the FTIR of Hunteria umbellata and Titanium (IV) oxide. The interpretation of the functional groups/ compounds, absorption band peaks wavenumber, and bonds are tabulated in Table 7. The composite applied formed barriers on the metal surface and the phytochemical interacted with the metal to enhance the stability and protection of the mild steel from corrosion. The composite acted as adsorption and formed a hydrophobic layer that repels moisture and ions that aid corrosion.

Table 6. Tabulated FTIR Spectrum analysis of titanium (IV) oxide nanopowder.

Functional group/compound	Absorption Peaks Wavenumber (cm⁻¹)	Type of bond
Hydroxyl, O-H	4339.40, 4261.92, 4206.00	Single
N-H	3766.00	single
Hydroxyl, H-bonded O-H stretch	3434.00	single
Methylene C-H asymmetric/symmetric stretch	2928.00	single
Methyl C-H asymmetric/ symmetric stretch. Saturated Aliphatic	2864.42	single
Transition metal carbonyls	1887.00	Double
Aldehyde	1726.50	Double
Carbonyl compound, Alkenyl C=C stretch	1637.46	Double
Fingerprint region	1448.20	single
O-H bend (phenol)	1376.26	single
OH in-plane bend	1296.00	single
Aromatic C-H -in-plane bend	1175.82	single
Aliphatic fluoro-compound C-F stretch	1099.00	single
Nitrate ion, C-O-O stretch	831.63	single
Ti-O-Ti	724.85	single
Sulfonate ion, C-S stretch Thioethers	655.21	single
C-S stretch, Ti-O	578.11	single
Fingerprint region Ti-O	408.22	single

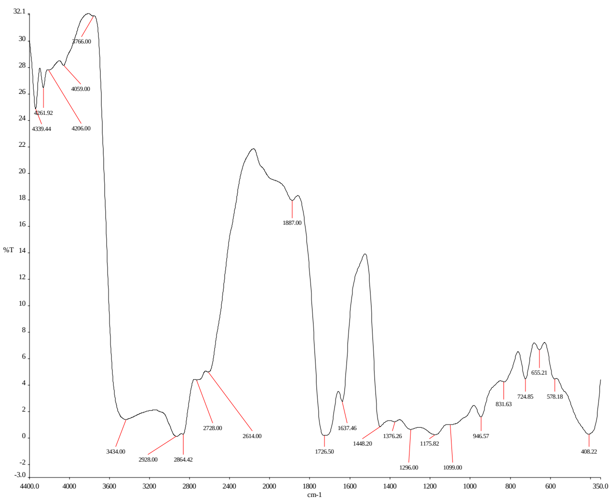


Fig. 3. FTIR spectrum for Titanium (IV) oxide.

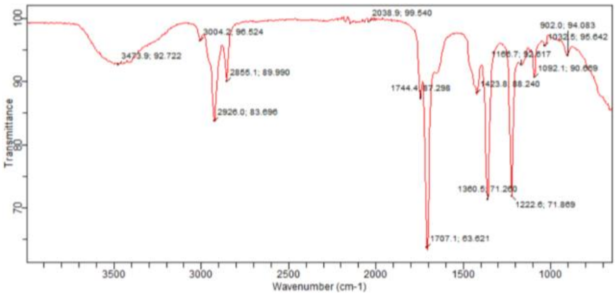


Fig. 4. FTIR Spectroscopy of Titanium (IV) oxide-hunteria umbellate nanocomposite.

Table 7. FTIR Spectroscopy of Titanium (IV) oxide-hunteria umbellata composite.

Functional group/compound	Absorption Peaks Wavenumber (cm⁻¹)	Type of bond
Dimeric OH stretch	3473.9, 3004.2	single
Methylene C-H asymmetric/symmetric stretch	2926.0, 2855.1	single
Transition metal, carbonyl compound	2038.9	Triple
Alkyl carbonate, carbonyl C=C, C=O, C=N	1744.4	Double
Carboxylic acid, carbonyl	1707.1	Double
Fingerprint region, Inorganic ions, carbonate ion	1423.8	Single
Nitrate ions, Inorganic ions	1360.5	Single
Aromatic phosphate (P-O-C) stretch	1222.6	Single
Sulfonate	1166.7	Single
Inorganic ions, silicate ions	1092.1, 1032.5, 902.0	Single

3.3 Scanning electron microscopy (SEM) surface morphology

The morphology of the surface of the mild steel, both the coated and uncoated specimens in acidic solutions of both 5% HCl and H_2SO_4 after 60 days are presented in figures (5a & 5b) for acidic solutions (HCl) and figures (6a &6b) for H_2SO_4. Figure 5a shows the image of a mild steel sample immersed in HCI and Figure 6a the sample in H_2SO_4 acidic solutions without Titanium (IV) oxide - Hunteria umbellata composite coating. The morphologies of mild steel in both acidic media showed corrosion pit cracks, voids, and defects visible on the surface as a result of high localized corrosion attack by acidic solutions (HCl and H_2SO_4) as shown in figures 5a and 6a. Figure 5b and figure 6b show the morphology of mild steel coated with Titanium (lV) oxide - Hunteria umbellata composite in HCI and H_2SO_4 acidic solutions respectively. The absence of a corrosion pit is noticeable in the samples coated. It is of important note that the composite coating serves as a protective cover as a result of Titanium (lV) oxide - Hunteria umbellata unique phytochemical bioactive properties.

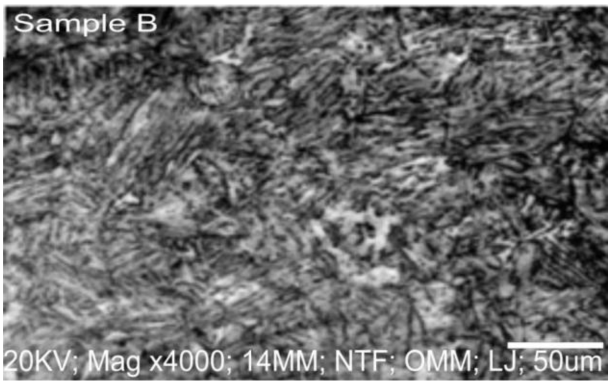


Fig. 5(a). SEM image of the mild steel (uncoated) after immersion in 5% HCl solution

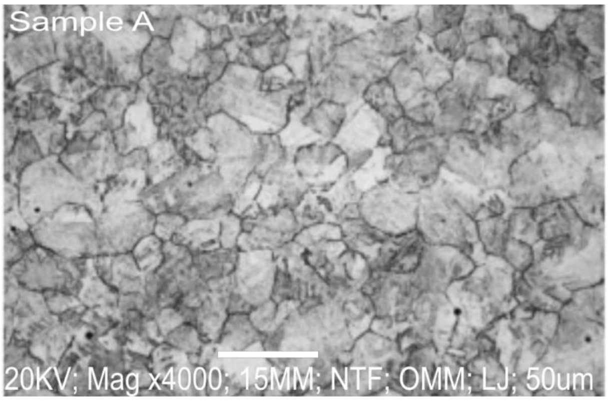


Fig. 5(b). SEM image of the mild steel sample A (coated) after immersion in 5% HCl solution.

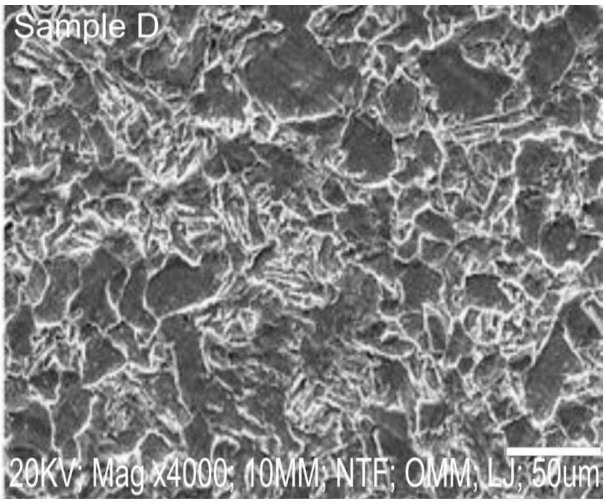


Fig. 6(a). SEM image of the mild steel sample D (uncoated) after immersion in 5% H_2SO_4 solution.

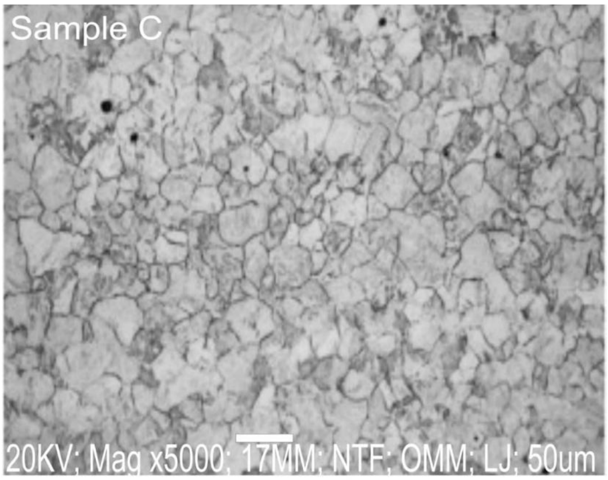


Fig. 6(b). SEM morphology of the mild steel sample C (coated) after immersion in 5% H_2SO_4 solution.

3.4 Electron dispersive X-ray spectroscopy

Figure 7 gives a detailed overview of the elemental composition of mild steel under study. The weight percentage of Fe is 67.20%. The alloy constituents such as carbon are 3.20%, oxygen is 10.30% due to trapped air in the mild steel during synthesis, zinc (6.25%), calcium (1.6%) magnesium (4.25%). Sodium (2.10%), chlorine (2.02%), silicon (0.50 %), and copper (2.17%).

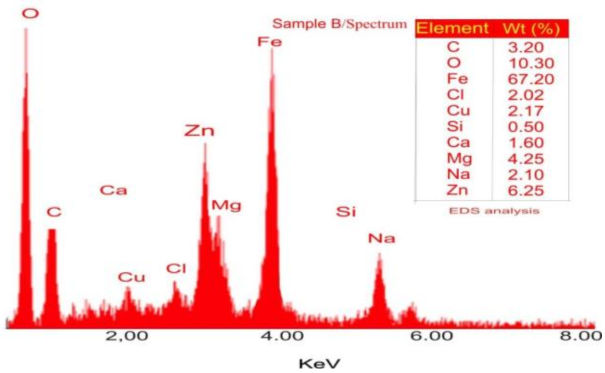


Fig. 7. EDX spectrum of the mild Steel.

3.5 X-ray structural analysis

Figure 8 is the X-ray structural pattern of titanium (IV) oxide. The peak positions are noticeable at 2θ = 23.24° 25.70°, 38.21°, 48.38°, 54.22°, 56.32°, and 63.00° corresponding to the crystallographic plane of miller indices (100), (101), (112), (200), (105), (106), and (204) respectively. The intensities of anatase TiO_2 obtained conform with the JCPDS Card no.78-2486 file. The result concurs with a similar result by [37]. The average crystallite size calculated is 43 nm. Figures 9a and 9b showed the structural pattern of XRD pattern of Titanium (IV) oxide- Hunteria umbellate nanocomposite. The peaks positions occurred at 2θ = 23.24° 25.70°, 38.21°, 48.38°, 54.22°, 56.32°, and 63.00° corresponding to the crystallographic plane of miller indices (100), (101), (112), (200), (105), (106), and (204) respectively. The phases conformed to standard anatase TiO_2.

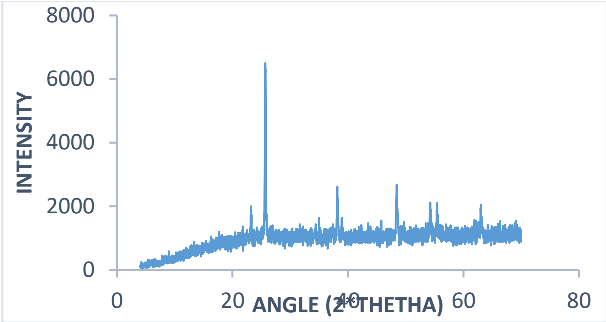
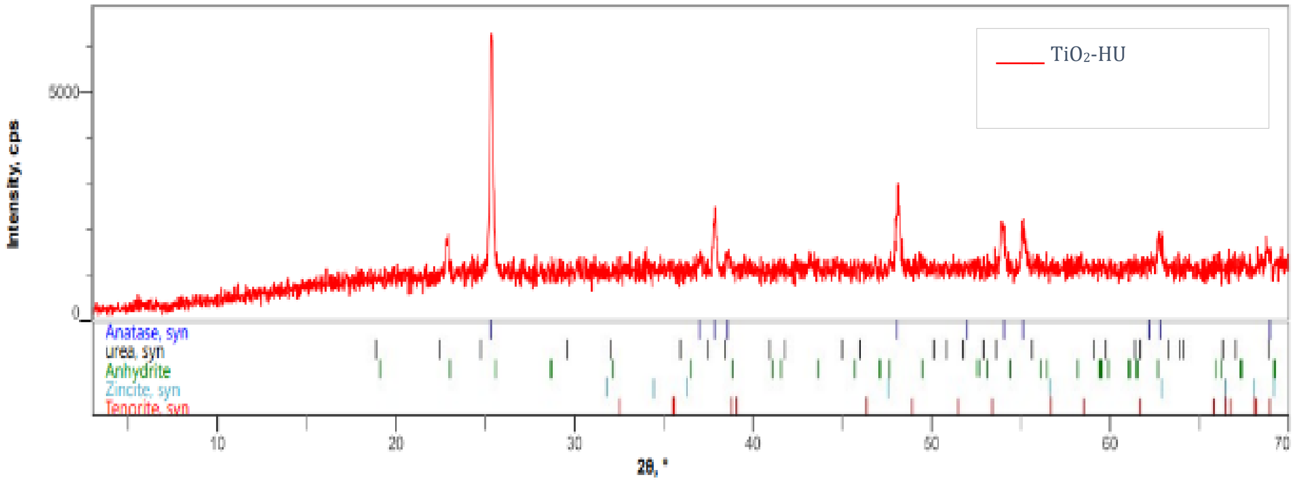
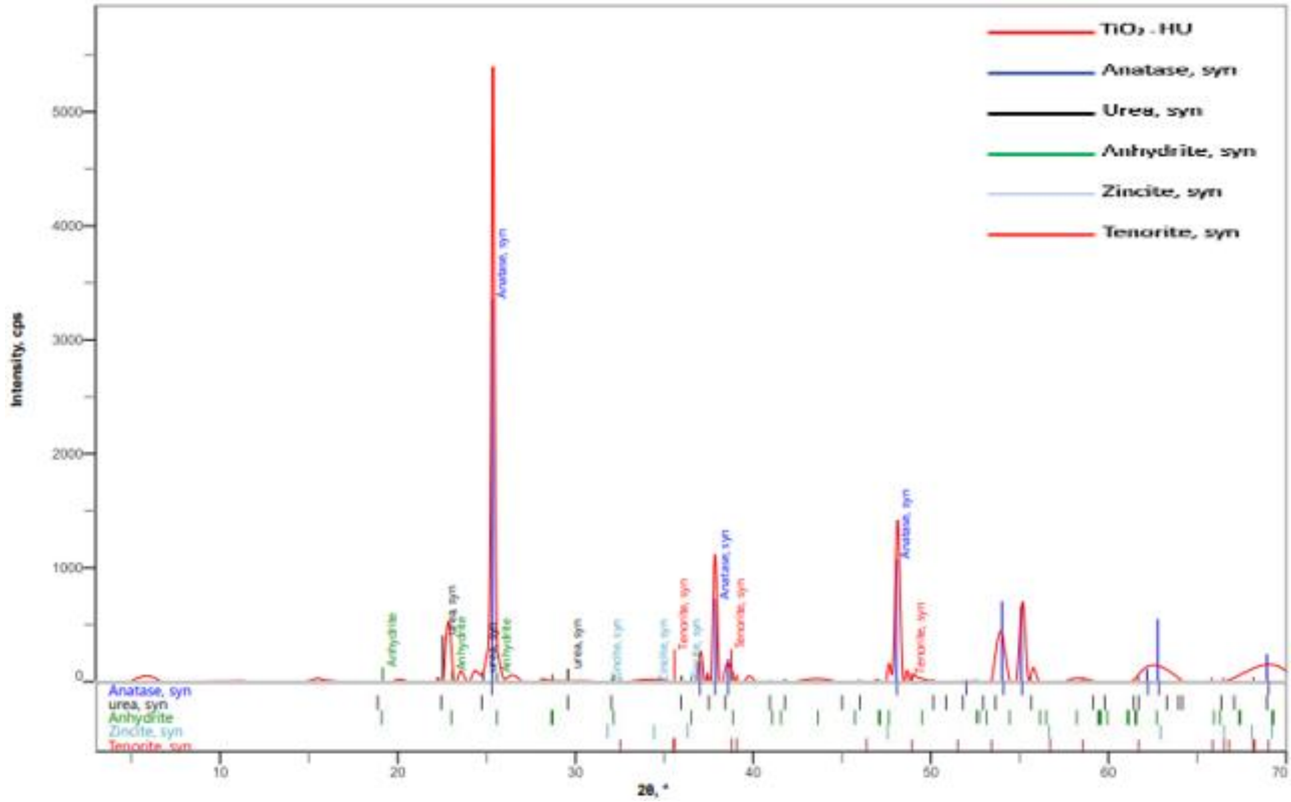


Fig. 8. XRD pattern of Titanium (IV) oxide nano powder.



(a) XRD pattern of Titanium (IV) oxide- Hunteria umbellate nanocomposite.



(b) Phase data view of nanocomposite

Fig. 9(a and b). XRD pattern of Titanium (IV) oxide- Hunteria umbellata nanocomposite.

4. CONCLUSION

Evaluation of Titanium (IV) oxide- Hunteria umbellata seed extracts properties has been experimented with as composite coating on mild steel in acidic media as a corrosion inhibitor. Hunteria umbellata seed extracts were used as a green corrosion-resistant material with Titanium (IV) oxide as a composite for coating on mild steel. The composite coating gives high protection in both HCI and H_2SO_4 acidic solutions. The composite inhibition efficiency was observed to be higher in HCl compared to the H_2SO_4 solution. The long-term performance efficiency of the composite coatings under different conditions needs to be evaluated and determined.

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REFERENCES

[1] M. R. Singh, P. Gupta, and K. Gupta, "The litchi (*Litchi chinensis*) peels extract as a potential green inhibitor in the prevention of corrosion of mild steel in 0.5 M H_2SO_4 solution," *Arabian Journal of Chemistry*, vol. 52, pp. 1035–1041, 2015. doi: 10.1016/j.arabjc.2015.01.002.

[2] C. Jones, D. Brown, and A. White, "Antimicrobial properties of TiO_2 nanoparticles in coatings for medical devices," *Journal of Materials Science: Materials in Medicine*, vol. 29, no. 2, p. 13, 2017.

[3] G. Bahlakeh, A. Dehghani, B. Ramezanzadeh, and M. Ramezanzadeh, "Highly effective mild steel corrosion inhibition in 1 M HCl solution by novel green aqueous mustard seed extract: Experimental, electronic-scale DFT and atomic-scale MC/MD explorations," *Journal of Molecular Liquids*, vol. 293, p. 111559, 2019. doi: 10.1016/j.molliq.2019.111559.

[4] M. Zhu et al., "Insights into the newly synthesized N-doped carbon dots for Q235 steel corrosion retardation in acidizing media: A detailed multidimensional study," *Journal of Colloid and Interface Science*, vol. 608, pp. 2039–2049, 2021. doi: 10.1016/j.jcis.2021.10.160.

[5] C. Verma, E. E. Ebenso, M. A. Quraishi, and C. M. Hussain, "Recent developments in sustainable corrosion inhibitors: Design, performance, and industrial scale applications," *Materials Advances*, vol. 2, no. 12, pp. 3806–3850, 2021. doi: 10.1039/d0ma00681e.

[6] S. I. Ezugha and C. C. Aralu, "Evaluation of adsorption and corrosion inhibition properties of *Solanum macrocarpon* leaves extract on mild steel in sulphuric acid solutions," *Springer Nature Applied Sciences*, vol. 5, p. 381, 2023. doi: 10.1007/s42452-023-05594-3.

[7] A. B. Radwan et al., "Electrospun highly corrosion-resistant polystyrene–nickel oxide superhydrophobic nanocomposite coating," *Journal of Applied Electrochemistry*, vol. 51, no. 11, pp. 1605–1618, 2021. doi: 10.1007/s10800-021-01603-8.

[8] M. B. Kermani and M. Moradpour, "A review of the inhibitory effect of green inhibitors on the corrosion of metals and alloys," *Royal Society Chemistry Advances*, vol. 8, no. 28, pp. 15704–15723, 2018.

[9] D. Kesavan, M. Gopiraman, and N. Sulochana, "Green inhibitors for corrosion of metals: A review," *Chemical Science Review and Letters*, vol. 1, no. 1, pp. 1–8, 2012.

[10] S. A. Umoren, Z. M. Gasem, and I. B. Obot, "Natural products for materials protection: Inhibition of mild steel corrosion by date seed extracts in acid media," *Industrial and Engineering Chemistry Research*, vol. 52, pp. 14855–14865, 2013.

[11] S. Kathiravan et al., "Inhibitory action of aqueous *Ruellia tuberosa* L. leaves extract on the corrosion of copper in HCl solution," *Journal of the Indian Chemical Society*, vol. 98, p. 100207, 2021. doi: 10.1016/j.jics.2021.100207.

[12] H. Li et al., "A green *Brassica oleracea* L. extract as a novel corrosion inhibitor for Q235 steel in two typical acid media," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 616, p. 126077, 2021. doi: 10.1016/j.colsurfa.2020.126077.

[13] M. Rathod, R. Minagalavar, and S. Rajappa, "Effect of *Artabotrys odoratissimus* extract, an environmentally sustainable inhibitor for mild steel corrosion in 0.5 M H_2SO_4 media," *Journal of the Indian Chemical Society*, vol. 99, p. 100445, 2022. doi: 10.1016/j.jics.2022.100445.

[14] X. Zhang et al., "Combined electrochemical/surface and theoretical assessments of *Rosa laevigata* extract as an eco-friendly corrosion inhibitor for copper in acidic medium," *Journal of the Taiwan Institute of Chemical Engineers*, vol. 136, p. 104408, 2022. doi: 10.1016/j.jtice.2022.104408.

[15] M. S. Al-Salhi et al., "Characterization of plants and seaweeds-based corrosion inhibitors against microbially influenced corrosion in a cooling tower water environment," *Arabian Journal of Chemistry*, vol. 16, p. 104513, 2023. doi: 10.1016/j.arabjc.2022.104513.

[16] B. Lin et al., "Passiflora edulis Sims peel extract as a renewable corrosion inhibitor for mild steel in phosphoric acid solution," *Journal of Molecular Liquids*, vol. 375, p. 121296, 2023. doi: 10.1016/j.molliq.2023.121296.

[17] A. Singh et al., "The effect of environmentally benign fruit extract of shahjan (*Moringa oleifera*) on the corrosion of mild steel in hydrochloric acid solution," *Chemical Engineering Communications*, vol. 199, no. 1, pp. 63–77, 2012.

[18] M. Khayatkashani et al., "Insight into the corrosion inhibition of *Biebersteinia multifida* root extract for carbon steel in acidic medium," *Science of the Total Environment*, vol. 836, p. 155527, 2022. doi: 10.1016/j.scitotenv.2022.155527.

[19] O. K. Abiola and A. O. James, "The effects of *Aloe vera* extract on corrosion and kinetics of corrosion process of zinc in HCl solution," *Corrosion Science*, vol. 52, no. 2, pp. 661–664, 2010.

[20] M. Mehdipour, B. Ramezanzadeh, and S. Y. Arman, "Electrochemical noise investigation of *Aloe* plant extract as a green inhibitor on the corrosion of stainless steel in 1 M H_2SO_4," *Journal of Industrial and Engineering Chemistry*, vol. 21, pp. 318–327, 2015.

[21] L. Liao, S. Mo, H. Luo, and N. Li, "Longan seed and peel as environmentally friendly corrosion inhibitor for mild steel in acid solution: Experimental and theoretical studies," *Journal of Colloid and Interface Science*, vol. 499, pp. 110–119, 2017. doi: 10.1016/j.jcis.2017.03.091.

[22] K. K. Alaneme, S. J. Olusegun, and O. T. Adelowo, "Corrosion inhibition and adsorption mechanism studies of *Hunteria umbellata* seed husk extract on mild steel immersed in acidic solutions," *Alexandria Engineering Journal*, 2015.

[23] K. K. Alaneme, Y. S. Daramola, S. J. Olusegun, and A. S. Afolabi, "Corrosion inhibition and adsorption characteristics of rice husk extract on mild steel immersed in 1 M H_2SO_4 and HCl solutions," *International Journal of Electrochemical Science*, vol. 10, pp. 3553–3567, 2015.

[24] A. Thomas, M. Prajila, K. M. Shainy, and A. Joseph, "A green approach to corrosion inhibition of mild steel in hydrochloric acid using fruit rind extract of *Garcinia indica* (Binda)," *Journal of Molecular Liquids*, vol. 312, 113369, 2020. doi: 10.1016/j.molliq.2020.113369.

[25] N. Karki, S. Neupane, D. K. Gupta, D. K. Das, S. Singh, G. M. Koju, Y. Chaudhary, and A. P. Yadav, "Berberine isolated from *Mahonia nepalensis* as an eco-friendly and thermally stable corrosion inhibitor for mild steel in acid medium," *Arabian Journal of Chemistry*, vol. 14, 103423, 2021. doi: 10.1016/j.arabjc.2021.103423.

[26] A. Philippe, R. Chahla, and M. Mohamed, "Corrosion inhibition of copper in 0.5 M NaCl solutions by aqueous and hydrolysis acid extracts of olive leaf," *Journal of Electroanalytical Chemistry*, vol. 859, 113834, 2020. doi: 10.1016/j.jelechem.2020.113834.

[27] J. Chen, Y. Wu, L. Guo, W. Li, B. Tan, and A. Brahmia, "Insight into the anti-corrosion mechanism of *Pisum sativum L.* leaves extract as the degradable inhibitor for Q235 steel in sulfuric acid medium," *Journal of the Taiwan Institute of Chemical Engineers*, vol. 143, 104664, 2023. doi: 10.1016/j.jtice.2022.104664.

[28] B. S. Swaroop, S. N. Victoria, and R. Manivannan, "*Azadirachta indica* leaves extract as inhibitor for microbial corrosion of copper by *Arthrobacter sulfureus* in neutral pH conditions: A remedy to the blue-green water problem," *Journal of the Taiwan Institute of Chemical Engineers*, vol. 64, pp. 269–278, 2016. doi: 10.1016/j.jtice.2016.04.007.

[29] L. Bi-lan, Z. Xin-xin, D. Tian-hu, Z. Chen, Z. Jia-hao, and X. Yu-ye, "Experimental and theoretical study on corrosion inhibition and adsorption performance of *Ipomoea batatas L.* leaf extract for mild steel," *Arabian Journal of Chemistry*, vol. 17, 105410, 2024. doi: 10.1016/j.arabjc.2023.105410.

[30] V. Vorobyova, M. Skiba, O. Chygyrynets, T. Pylypenko, T. Motronyuk, and Y. Fateev, "Inhibition efficiency of apricot pomace extract as a 'green' corrosion inhibitor," *Materials Today: Proceedings*, vol. 50, pp. 456–462, 2021. doi: 10.1016/j.matpr.2021.11.292.

[31] C. Xu, W. Li, B. Tan, X. Zuo, and S. Zhang, "Adsorption of *Gardenia jasminoides* fruits extract on the interface of Cu/H_2SO_4 to inhibit Cu corrosion," *Experimental and Theoretical Study*, vol. 345, 116996, 2022. doi: 10.1016/j.molliq.2021.116996.

[32] B. Lin, J. Shao, Y. Xu, Y. Lai, and Z. Zhao, "Adsorption and corrosion of renewable inhibitor of pomelo peel extract for mild steel in phosphoric acid solution," *Arabian Journal of Chemistry*, vol. 14, no. 5, 103114, 2021. doi: 10.1016/j.arabjc.2021.103114.

[33] J. Wang, X. Ma, M. Tabish, and J. Wang, "Sunflower-head extract as a sustainable and eco-friendly corrosion inhibitor for carbon steel in hydrochloric acid and sulfuric acid solutions," *Journal of Molecular Liquids*, vol. 367, 120429, 2022. doi: 10.1016/j.molliq.2022.120429.

[34] Q. Wang, H. Zheng, L. Liu, Q. Zhang, X. Wu, Z. Yan, Y. Sun, and X. Li, "Insight into the anti-corrosion behavior of *Reineckia carnea* leaves extract as an eco-friendly and high-efficiency corrosion inhibitor," *Industrial Crops and Products*, vol. 188, 115640, 2022. doi: 10.1016/j.indcrop.2022.115640.

[35] P. G. Rao, M. Iwasa, T. Tanaka, I. Kondoh, and T. Inoue, "Title of the paper," *Scripta Materialia*, vol. 48, p. 437, 2003.

[36] H. Liu, H. Ye, and Y. C. Zhang, "Title of the paper," *Colloids and Surfaces A*, vol. 315, p. 1, 2008.

[37] X. He, G. Zhang, Y. Cai, and L. Wu, "Title of the paper," *Advance Science Letters*, vol. 18, no. 43, 2012.

[38] P. Kamaraj, S. Devikala, and M. Arthanareeswari, "Fabrication, characterization and application of polymethymethacrylate/titanium dioxide composite coatings for corrosion inhibition," *International Journal of Advanced Scientific and Technical Research*, vol. 4, no. 1, 2014.

[39] N. J. Mohammed, K. O. Norinsan, J. J. A. Ahmed, *et al.*, "Date palm seed extract for mild steel corrosion prevention in HCl medium," *Separations*, vol. 10, no. 1, p. 54, 2023. doi: 10.3390/separations10010054.

[40] A. Smith, B. Johnson, and J. Doe, "Sol-gel synthesis of TiO_2 nanoparticles for enhanced corrosion resistance of steel substrates," *Journal of Coatings Technology and Research*, vol. 12, no. 5, pp. 895–902, 2015.

[41] M. Li, M. Zhao, J. Chen, *et al.*, "Enhanced corrosion resistance of epoxy coating containing TiO_2 nanoparticles modified with silane coupling agent," *Progress in Organic Coatings*, vol. 101, pp. 253–263, 2016.

[42] A. Garcia, M. Rico, R. Gonzalez, *et al.*, "Antibacterial activity of composite coatings with TiO_2 nanotubes and silver nanoparticles on 316L stainless steel," *Applied Surface Science*, vol. 434, pp. 1325–1332, 2018.

[43] R. Patel, S. Kansara, H. Bajaj, and A. Mukhopadhyay, "Plant extract mediated synthesis of TiO_2 nanoparticles for corrosion control applications," *Journal of Molecular Liquids*, vol. 277, pp. 600–611, 2019.

[44] ASTM, "Standard guide for laboratory immersion corrosion testing of metals," ASTM NACE/ASTMG31-12a2012, ASTM International, West Conshohocken, PA, 2012. doi: 10.1520/G0031-12A.

[45] J. Coates, "Interpretation of infrared spectra, a practical approach," *Encyclopedia of Analytical Chemistry*, vol. 12, pp. 10815–10837, 2000.

[46] A. B. D. Nandiyanto, R. Oktiani, and R. Ragadhita, "How to read and interpret FTIR spectroscope of organic material," *Indonesian Journal of Science & Technology*, vol. 4, no. 1, pp. 97–118, 2019.