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Effect of Hybrid Eco-Friendly Plant Extract for Corrosion Mitigation of Gray Cast Iron in HCL

O. O. Oke[1,2*], A. O. Aluko[1,3], F. O. Ogundeji[1,2]

[1]Mineral and Petroleum Resources Engineering Department, The Federal Polytechnic Ado Ekiti, Nigeria
[2]Metallurgical and Materials Engineering Department, Federal University of Technology, Akure.
[3]Mechanical Engineering Science Department, University of Johannesburg, Box 524, Asuckland Park 2029
Johannesburg, Gauteng, South Africa
*Corresponding author (Email: okenature2@yahoo.com , alayrehoboth@gmail.com)

ABSTRACT

This study investigated the corrosion resistance of gray cast iron in 0.1 M HCl using a hybrid inhibitor system composed of water hyacinth extract and zinc oxide nanoparticles. Electrochemical impedance spectroscopy (EIS), Bode plot analysis, phase angle interpretation, and surface characterization techniques (SEM and EDS) were employed to evaluate inhibitor performance. The results revealed that the combined inhibitors achieved an efficiency of 82.2%, surpassing many previously reported natural inhibitors. Nyquist plots demonstrated a significant increase in charge transfer resistance (Rct), while Bode plots confirmed enhanced impedance at low frequencies and more pronounced capacitive behavior, indicative of a uniform protective film. SEM and EDS analyses further validated the formation of a smoother, compact surface layer with successful adsorption of inhibitor species. These findings corroborate recent reports emphasizing the synergistic benefits of combining organic phytochemicals with inorganic nanoparticles for sustainable corrosion protection Overall, this research highlights the potential of hybrid green inhibitors to deliver long-term, environmentally friendly corrosion prevention in industrial applications.

Keywords— **Corrosion , Electrochemical ,Grey Cast Iron(GCI) , Inhibitors, Water Hyacinth**

I. INTRODUCTION

Gray cast iron (GCI) is widely valued in industry for its versatility, excellent casting properties, and cost-effectiveness—typically 20–40% cheaper than steel—while also offering durability and fire resistance for both domestic and commercial applications. Recent studies highlight its role in automotive components and ongoing innovations to enhance performance and reduce production costs[20][25]. It is a complex material including stable and meta-stable phases, as well as solution components that impact the degree and stability of desired qualities that other alloys do not have [22]. GCI features a low rate of thermal expansion, outstanding damping capabilities (tool machines), strong, stiffness, resistance to thermal fatigue, good anti-friction qualities, 100% recyclability, and resistance to compressive loads. 3-4 times of resistance to tensile stresses [5] . The machinability of gray cast iron (GCI) depends on its microstructural constituents, which are controlled by the alloy's chemical composition before casting and the cooling rate during solidification.

GCI is characterized by flake graphite dispersed within an iron matrix enriched with silicon, and these features govern its mechanical and machining behavior [15][7]. Higher silicon levels enhance graphite synthesis, whereas lower silicon levels increase iron carbide production . Gray cast iron (GCI) has long been utilized in components such as flywheels, pulleys, machine frames, automotive cylinders, pistons, water and soil pipes, flange couplings, ingot molds, and large equipment exposed to compressive stresses and vibrations. Modern applications extend to pressure systems including cylinder blocks, manifolds, compressors, and pumps. More recently, cast irons have gained traction in the wind energy sector, serving as structural materials for rotor hubs and nacelles. Despite its mechanical strength, affordability, and ease of manufacture, GCI remains prone to corrosion, which poses significant economic and environmental challenges. Its susceptibility to degradation, particularly in acidic or extreme conditions, continues to limit long-term durability and performance [14][4].Corrosion inhibitors are substances that may reduce or prevent metal corrosion, which is crucial for minimizing mineral dissolution and acid consumption.[3].

These inhibitors are split into two categories: inorganic and organic. These inhibitors include aromatic rings and heteroatoms like sulfur (S), oxygen (O), and nitrogen (N), which may cause the molecules to release lone electron pairs, creating coordination bonds with the transition metal and causing chemical adsorption [6]. Green corrosion inhibitors are biodegradable, devoid of heavy metals and other toxic substances. Some researchers have successfully employed naturally occurring chemicals to minimize metal corrosion in acidic and alkaline conditions [1]. This could be attributed to their better electrical and thermal conductivity, which alludes to the cryogenic properties employed in valves, wellhead stems, and seals. Over the last few decades, there has been a rise in environmental awareness of the need to limit the usage of chemical-based corrosion inhibitors. The usage of green chemistry principles is actively advocated in both research and industry.

Water hyacinth (Eichhornia crassipes) is an aquatic plant species recognized for its quick growth and capacity to survive in a range of aquatic habitats, including freshwater bodies, ponds, and rivers [21]. In addition to its ecological utility, water hyacinth has spurred studies in a range of sectors, including wastewater treatment, phytoremediation, and sustainable material development. A recent study has emphasized the potential of water hyacinth extracts as corrosion inhibitors for metals such as steel, aluminum, and copper in acidic solutions due to the presence of bioactive chemicals with inhibitory capabilities [12].

Zinc oxide (ZnO) is another material that has been widely explored for its corrosion prevention qualities due to its cheap cost, chemical stability, and non-toxicity[18]. Zinc oxide, being a semiconductor material, has intrinsic corrosion resistance and has been utilized in a number of forms, including nanoparticles, to inhibit corrosion on metallic substrates.

II. MATERIALS AND METHODS

A. Plant Samples Collection and Preparation

The water hyacinth leaves were sourced from Ilaje local government Ondo state, Nigeria. After harvesting, the collected plant samples were rinsed with tap water many times to remove the dust and then washed with distilled water, dried in oven at 70°C till having constant dry weight [8]. About 20 grams of crushed leaves were weighed and steeped in 100 ml of ethanol for 48 hours. The extract was produced by filtering the mixture. To eliminate any ethanol from the material, the filtrates were dried. The resulting extract solution was used to create different concentrations of the extract by dissolving 5, 10, 15, 20, and 25 g/l of extract in 0.1 mL of HCL.

B. Electrochemical Impedance Spectroscopy (EIS)

EIS measurements were carried out at an open-circuit potential from 100 kHz to 10 MHz, with 10 points logarithmically spaced per frequency decade and a 10 mV amplitude sinusoidal signal perturbation. After electrochemical impedance measurements polarization experiment was conducted varying the concentration of the inhibitor at a scan rate of 10 mV/s between the voltages of ±1.5 V. Electrochemical tests were performed three times to ensure the reproducibility of the experiment under the same conditions.

C. Scanning Electron Microscopy (SEM)

The surface morphology and elemental distribution on the selected metals before and after immersion with and without the presence of inhibitors were examined with scanning electron microscopy equipped with EDX.

D. Preparation of Inorganic Inhibitor (ZnO) and water hyacinth extract

The zinc oxide was bought from a lab within Ado metropolis and was measured into different beakers respectively.

1st Run: 20g of zinc oxide + 25g of water hyacinth extract
2nd Run: 20g of zinc oxide + 20g of water hyacinth extract
3rd Run: 20g of zinc oxide + 15g of water hyacinth extract
4th Run: 20g of zinc oxide + 10g of water hyacinth extract
5th Run: 20g of zinc oxide + 5g of water hyacinth extract
6th Run: Blank

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III. RESULTS

Table 1. Elemental Composition of Cast Iron

Elements	C	Si	Mn	P	S	Cr	Ni	Li	W	Ti	Cu
Composition	3.01	1.07	0.6	0.03	0.05	12.9	0.07	0.05	0.031	0.005	0.039

Table 2. Phytochemical screening of water hyacinth (Qualitative screening)

Secondary Metabolie	**Test**	**Colour changes**	**Inference**
Alkaloid	Mayers test	Greenish Yellow	++ve
Saponin	Frothing test	Nill	-ve
Phenol	Swallowsh	Reddish brown	+++ve
Flavonoid	Ferric chloride test	Yellowish green	+++ve
Tannin	Fecl3 tes	Brown	+ve
Terperniod		Light yellow	+ve
Oxalate		Nill	-ve
Quinone			-ve

Table 3. Phytochemical screening of water hyacinth (Quantitative screening)

Secondary metabolite	**Constituent**
Alkaloid	1.9
Tannin	1.4
Flavonoid	3.9
Terpernoid	3.25
Phenon	5.0

Table 4: Electrochemical impedance spectroscopy (EIS) result

Concentration	Rs (ohm)	Rct (ohm)	Yo1(S *s^a)	n1	Rf (ohm)	Yo2(S*s^a)	n2	Goodness of Fit	%IE
0.1M HCl Blank Fe	1.91E-01	2.65	1.62E-03	9.25E-01	2.17E-06	2.248	4.57E-01	1.38E-03	0.00
0.1M HCl 5g/20g ZnO Fe	2.26E-01	3.425	2.50E-03	9.13E-01	2.29E-02	4.766	2.47E-02	1.86E-04	22.628
0.1M HCl 10g/**20g ZnO Fe**	3.95E-01	8.976	0.14E-03	9.00E-01	2.10E-01	0.12E-01	1	1.14E-04	70.477
0.1M HCl 15g/20g ZnO Fe	3.80E-01	14.89	8.52E-04	8.97E-01	1.78	4.93E-04	9.03E-01	3.08E-04	82.203
0.1M HCl 20g/20g ZnO Fe	5.71E-01	7.019	5.89E-04	9.57E-01	2.804	1.18E-03	1	9.23E-04	62.245
0.1M HCl 25g/20g ZnO Fe	2.89E-01	7.961	2.80E-04	8.72E-01	1.137	8.43E-04	9.29E-01	9.28E-04	66.713

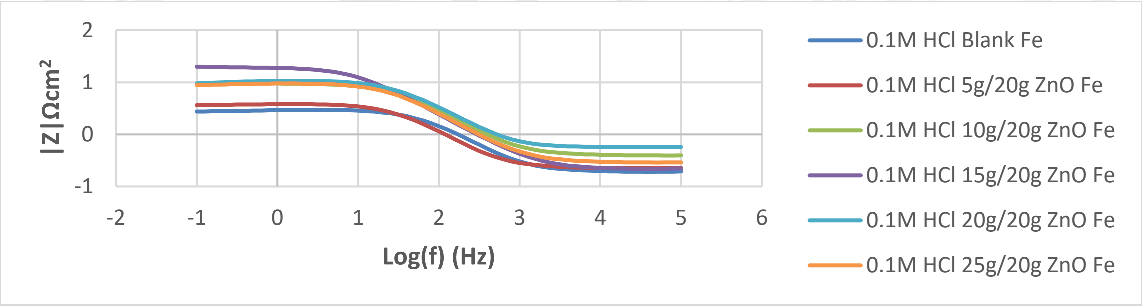


Fig. 1: Bode plot of Grey Cast Iron 0.1M HCl in the varying concentrations of Water hyacinth extracts and Zinc oxide

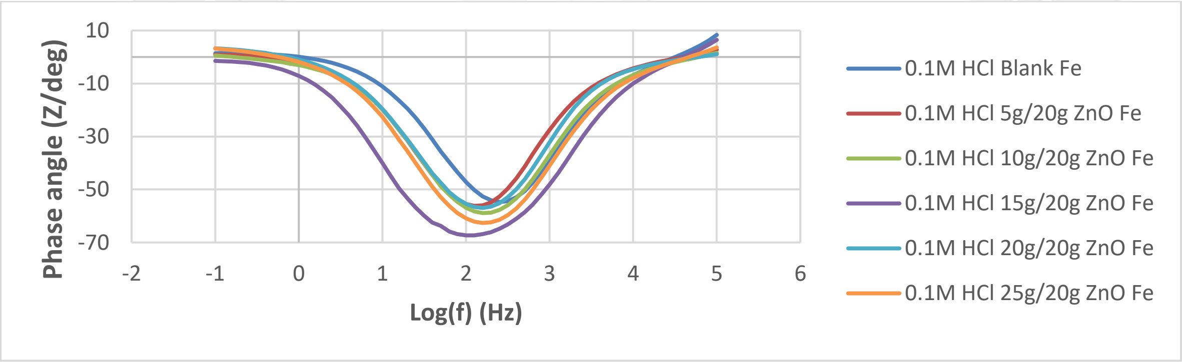


Fig. 2: Phase angle Bode spectra of GREY CAST IRON in 0.1M Hcl in the varying concentrations of Water hyacinth extracts and Zinc oxide

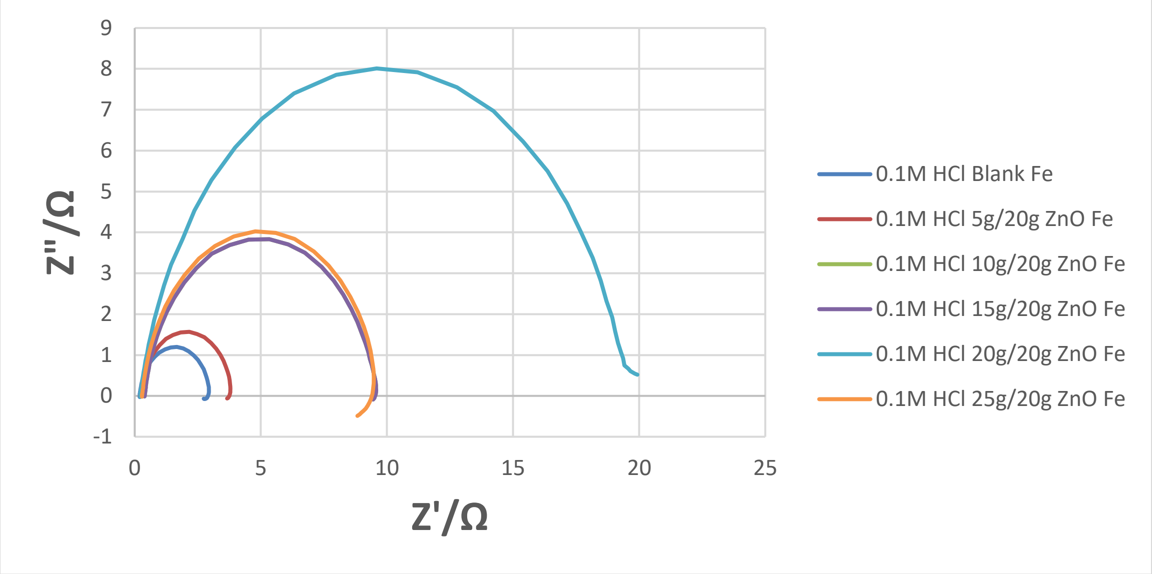


Fig. 3: Nyquist plot of Grey Cast Iron in 0.1M Hcl in the varying concentration of the water hyacinth extracts

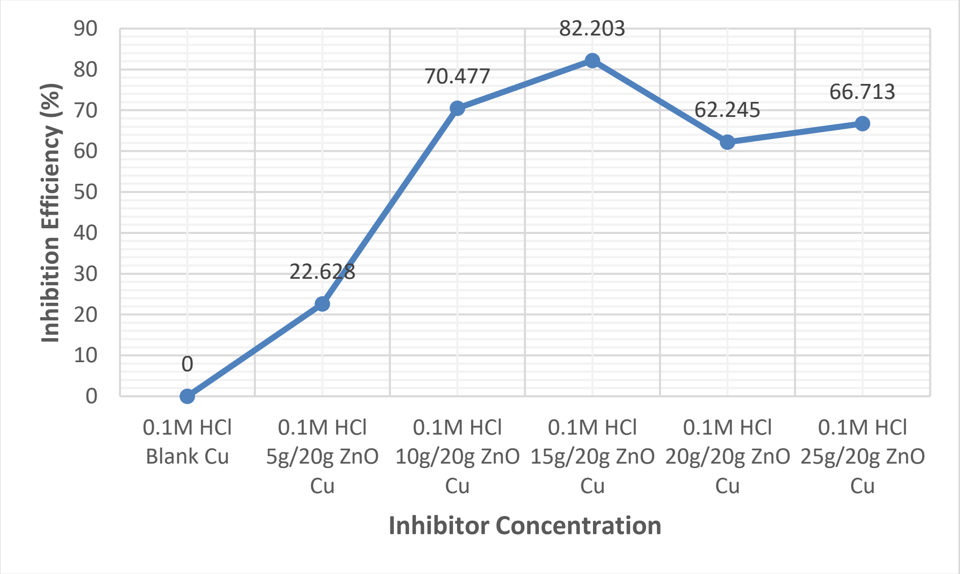


Fig. 4: Electrochemical impedance spectroscopy (EIS) Result Plot of Inhibition Efficiency against inhibitor concentration of Grey Cast Iron in 0.1M Hcl in the varying concentrations of Water hyacinth extracts and Zinc oxide

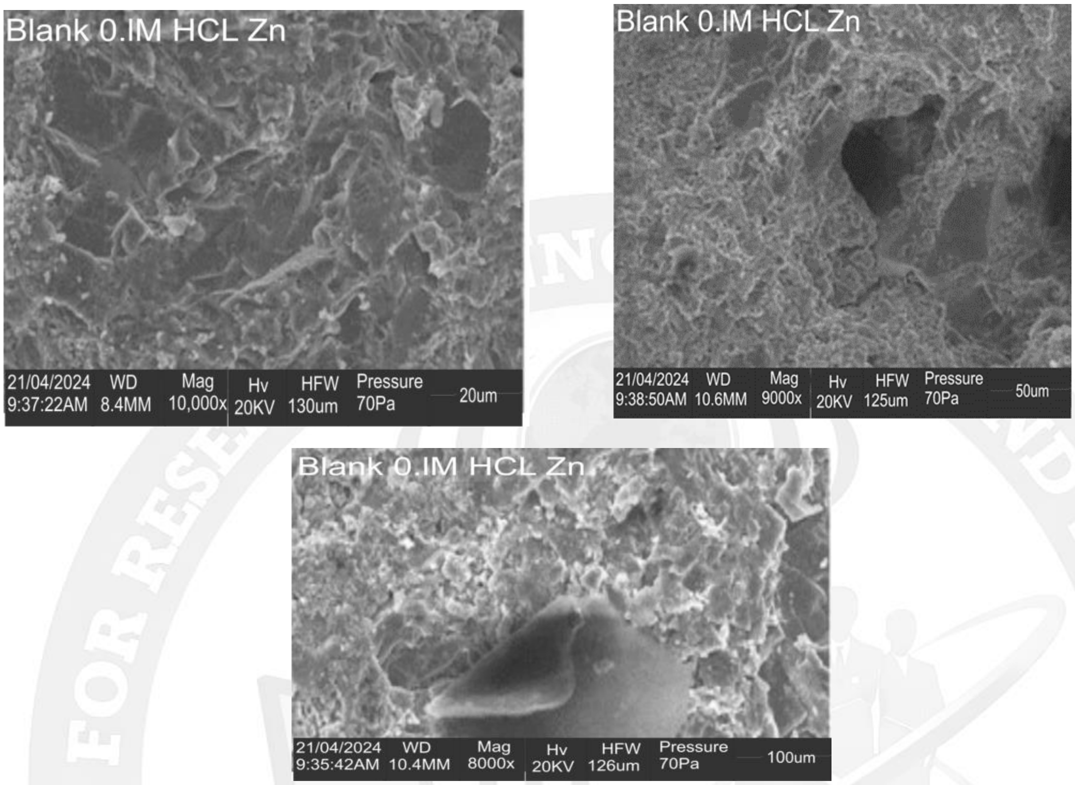


Fig. 5: SEM Micrograph of the blank Sample with three magnifications (20 µm, 50 µm and 100 µm)

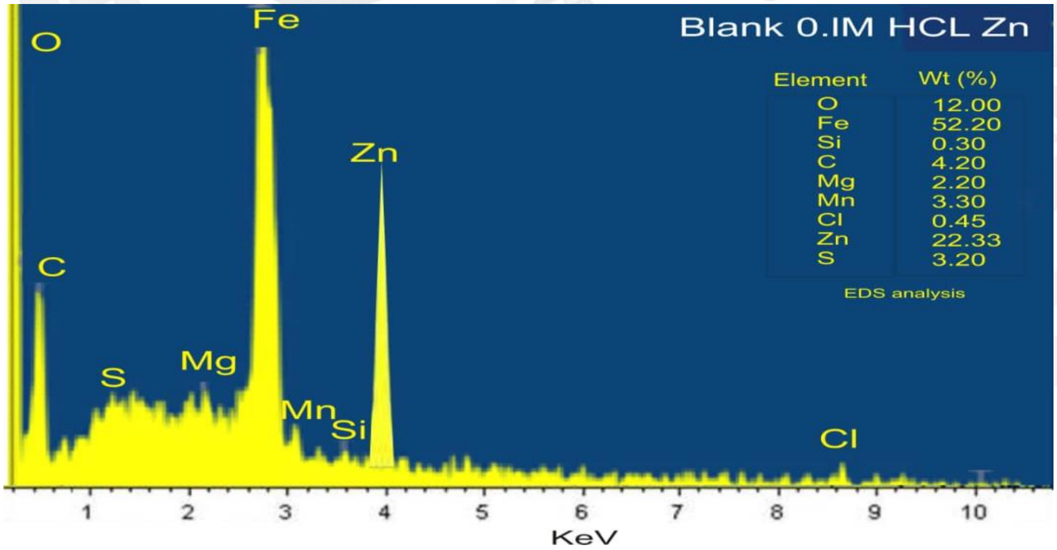


Fig. 6: EDX Spectrum of the blank Sample and with its chemical composition

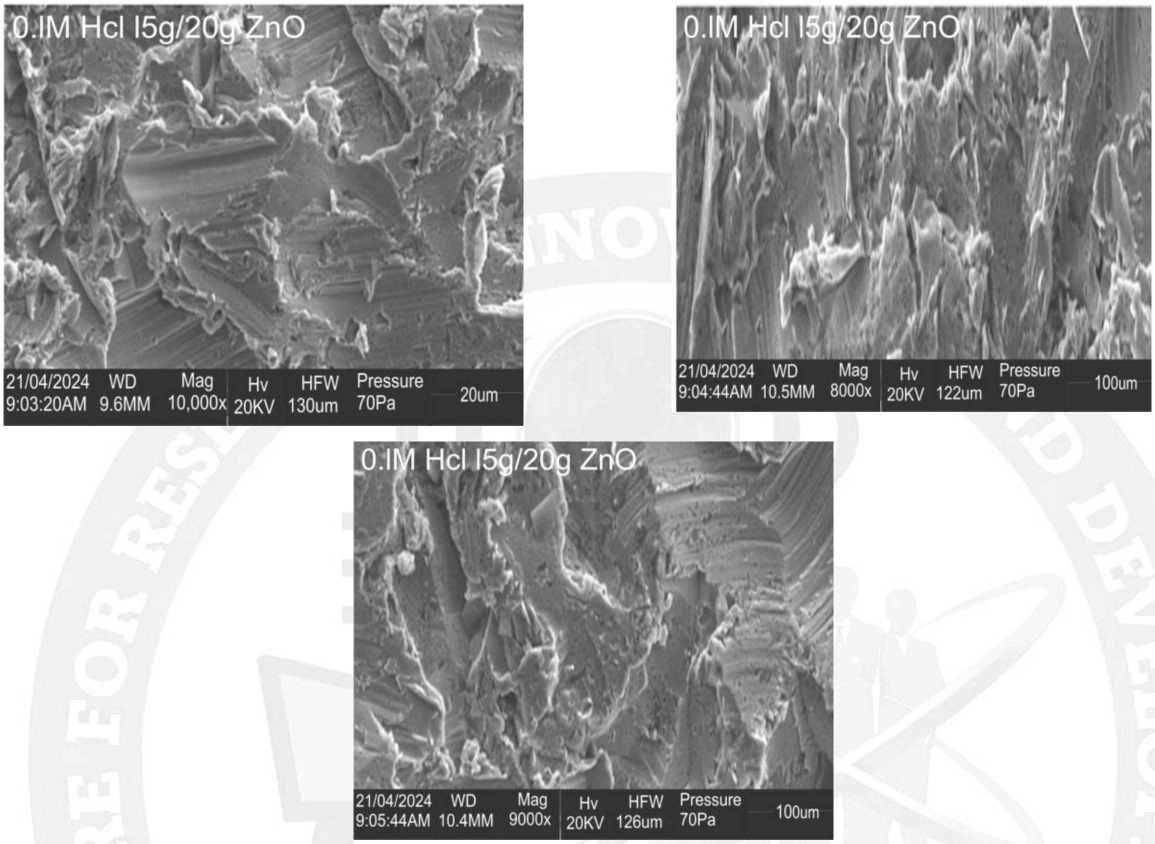
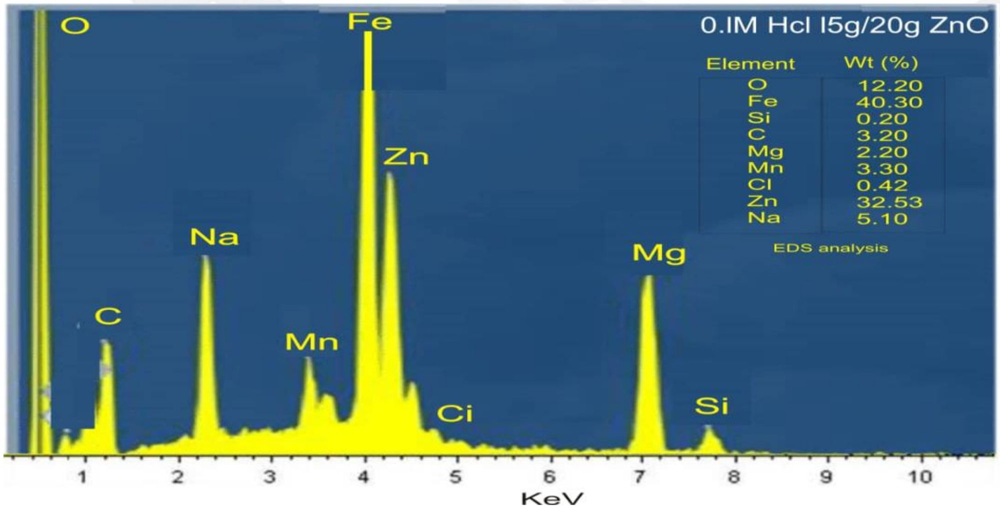


Fig. 7: SEM Micrograph of the 15g/20g ZnO immersed concentrated Sample with three magnification



Element	Wt (%)
O	12.20
Fe	40.30
Si	0.20
C	3.20
Mg	2.20
Mn	3.30
Cl	0.42
Zn	32.53
Na	5.10

Fig. 8: EDX Spectrum of the 15g/20g ZnO concentrated Sample with its chemical composition

IV. DISCUSSION

A. Inhibition Efficiency of Water Hyacinth and Zinc Oxide

The inhibitory efficiency of water hyacinth extract combined with zinc oxide nanoparticles was evaluated using electrochemical impedance spectroscopy (EIS). Gray cast iron samples immersed in 0.1 M HCl, with and without inhibitors, exhibited distinct electrochemical responses. The presence of the hybrid inhibitor system significantly increased charge transfer resistance, thereby limiting the electrochemical processes responsible for corrosion. This synergistic effect arises from phytochemical adsorption and nanoparticle reinforcement, which collectively form a compact protective film at the metal electrolyte interface. Such findings are consistent with recent studies highlighting the effectiveness of plant-based extracts and ZnO nanomaterials in enhancing corrosion resistance [23].

B. Synergistic Effects of Combined Inhibitors

The usage of water hyacinth extract and zinc oxide was tested to evaluate if a synergistic effect may increase corrosion inhibition. The electrochemical measurements indicated a substantial increase in inhibition effectiveness when both inhibitors were administered simultaneously.

The Rct value for the combined inhibitors was substantially larger, with an overall inhibition efficiency of 82.203%. This synergistic impact is owing to the complementing impacts of organic chemicals in water hyacinth extract and inorganic zinc oxide nanoparticles. The organic molecules adsorb onto the metal surface, providing initial coverage, while the nanoparticles fill in the gaps, resulting in a more uniform and robust barrier [24].

The enhanced surface protection indicated in EIS data confirms the synergistic interaction because the combined inhibitors present bigger semicircles in the Nyquist plots, implying higher impedance and lower corrosion rates. This conclusion is consistent with earlier studies demonstrating that combining organic and inorganic inhibitors can boost corrosion protection by generating a denser and more durable protective covering [16].

C. Surface Morphology Analysis using SEM

Scanning Electron Microscopy (SEM) was employed to evaluate the surface morphology of gray cast iron exposed to 0.1 M HCl, with and without inhibitors. The uninhibited sample exhibited severe corrosion damage, including deep pits and extensive roughening, characteristic of active acid attack. In contrast, specimens treated with water hyacinth extract or zinc oxide nanoparticles displayed markedly reduced surface degradation, with smoother morphologies and fewer pits. This improvement demonstrates that the inhibitors effectively suppressed corrosion by forming a protective barrier at the metal–electrolyte interface, consistent with recent findings on green inhibitors and nanoparticle-assisted film formation [11][2].

The SEM pictures of the 15g/20g ZnO immersion concentrated sample, as shown in figure 7, demonstrated an even higher reduction in surface roughness and pitting. The surface appeared entirely unharmed, with only tiny indications of corrosion. This research reveals that the synergistic combination of water hyacinth extract and zinc oxide delivers higher protection by generating a more homogenous and adherent protective layer on the gray cast iron surface.

D. Elemental Composition Analysis using EDS

EDS was utilized alongside SEM to analyze the elemental composition of gray cast iron surfaces following exposure. The EDS analysis was meant to detect corrosion products and establish the distribution of inhibitor-related components. Figure 6 shows the EDS spectra of uninhibited samples, which exhibited high levels of oxygen and chlorine, suggesting corrosion products such as iron oxide and iron chloride. These elements are characteristic of the aggressive corrosion process in an acidic environment. However, the inhibited samples demonstrated a considerable decline in chlorine and oxygen content, showing that the inhibitors were effective in preventing corrosion. The EDS spectra of the 20g/20 g ZnO immersion concentrated sample, as shown in figure 8, indicated the presence of both carbon and zinc, suggesting that the inhibitors' organic and inorganic components were effectively combined on the metal surface. This combination provided a more comprehensive protective barrier, as demonstrated by the reduced amounts of oxygen and chlorine [17].

E. Electrochemical Impedance Spectroscopy (EIS) Results

Electrochemical impedance spectroscopy (EIS) results reveal that the mixed water hyacinth extract with ZnO nanoparticles markedly improves the corrosion resistance of gray cast iron in 0.1 M HCl. The blank sample exhibited low charge transfer resistance ($R_{ct} = 2.65\ \Omega$) and no inhibition efficiency, indicating severe corrosion. Progressive addition of ZnO increased Rct, peaking at 14.89 Ω with 15 g ZnO, corresponding to the highest inhibition efficiency (82.2%). This enhancement reflects the synergistic adsorption of phytochemicals and ZnO nanoparticles, forming a compact protective film. At higher concentrations (20–25 g), efficiency declined, likely due to nanoparticle agglomeration and film instability, consistent with recent findings on hybrid organic–inorganic inhibitors [23][19].

F. Comparison with Previous Studies

When compared to earlier investigations, the combination of water hyacinth extract and zinc oxide nanoparticles demonstrated superior inhibitory efficacy. For instance, natural extracts such as henna

(*Lawsonia inermis*) have been reported to achieve inhibition efficiencies of approximately 80% in acidic environments[13]. In contrast, the present study achieved 82% efficiency, underscoring the synergistic effect of combining organic phytochemicals with inorganic nanoparticles. Furthermore, the Bode phase angle plots revealed more pronounced capacitive behavior than those observed in single-inhibitor systems, signifying the formation of a more compact and protective layer. This enhancement in Bode plot characteristics, particularly the stronger peaks at low frequencies, corresponds with higher charge transfer resistance (Rct) values in Nyquist plots, confirming the superior corrosion protection afforded by the hybrid inhibitor system. These findings are consistent with recent reports on green inhibitors reinforced with nanomaterials, which highlight the advantages of hybrid approaches in achieving durable corrosion resistance [9][10].

V. CONCLUSION

This research investigated the corrosion resistance of gray cast iron in an acidic environment using a hybrid inhibitor system composed of water hyacinth extract and zinc oxide nanoparticles. Electrochemical methods, including impedance spectroscopy (EIS), Bode plot analysis, phase angle interpretation, and surface characterization techniques such as SEM and EDS, were employed to evaluate performance. The results demonstrated that the combined inhibitors achieved an efficiency of 82.2%, surpassing many previously reported natural inhibitors. Nyquist plots revealed a significant increase in charge transfer resistance (Rct), while Bode plots confirmed enhanced impedance at low frequencies and more pronounced capacitive behavior, indicative of a uniform protective film. SEM and EDS analyses further validated the formation of a smoother, compact surface layer with successful adsorption of inhibitor species. These findings corroborate recent studies that highlight the synergistic benefits of combining organic phytochemicals with inorganic nanoparticles for sustainable corrosion protection [9][10]. Overall, this work underscores the potential of hybrid green inhibitors to deliver long-term, environmentally friendly corrosion prevention in industrial applications.

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