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Eco-friendly Synthesis of Silver Nanoparticles from African Fan Palm (*Borassus aethiopum*) Leaf Extract for Corrosion Inhibition of Mild Steel in 1 M HCl: A Weight Loss Analysis

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Abstract

This study investigates the green synthesis, characterization, and corrosion inhibition behavior of silver nanoparticles (AgNPs) derived from African Fan Palm (*Borassus aethiopum*) dry leaf extract using aqueous extraction method. The phytochemical constituents of the extract served as natural reducing and stabilizing agents, facilitating the eco-friendly formation of stable, nanosized AgNPs. UV-Visible spectroscopy exhibited a characteristic surface plasmon resonance peak at 283 nm, confirming nanoparticle formation with blue shift, while FTIR spectra revealed that biomolecules present in the extract were actively involved in both silver ion reduction and nanoparticle stabilization through surface adsorption. The corrosion inhibition efficiency of the synthesized AgNPs was evaluated on mild steel in a corrosive medium (1 M HCl) at varying concentrations (100 ppm, 150 ppm, 200 ppm, 250 ppm, 300 ppm, and 400 ppm). The results showed a direct relationship between inhibitor concentration and inhibition efficiency, attaining a maximum efficiency of 80.6%, surface coverage of ≈ 0.81, and a minimum corrosion rate of 0.208 mg cm^{-2} h^{-1} (2.32 mm/yr) at 400 ppm after 24 hours of immersion. Although the optimum inhibitor concentration was not attained within the studied range, the synthesized AFP-AgNPs demonstrated excellent adsorption and protective characteristics. These findings confirm that Borassus aethiopum leaf extract serves as an effective, sustainable, and eco-friendly source for AgNP synthesis, with promising potential for corrosion inhibition.

Keywords: Eco-friendly, synthesis, silver nanoparticles, *Borassus aethiopum*, corrosion inhibition, mild steel

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Introduction

Corrosion refers to the erosion of a material due to chemical, biochemical or electrochemical interactions with its environment, resulting in a loss of material mass over time (Ogunleye et al., 2021). Corrosion entails electrochemical reactions that transform metal into oxide or hydroxide, hence degrading the material's viability. In mild steel (MS), this process often commences with the production of rust (iron oxide), resulting in a reduction of thickness and alterations in the mechanical characteristics of the steel (Ali et al., 2023).

Corrosion inhibition refers to the process of decreasing the rate at which a metal corrodes by adding chemical substances that adsorb onto its surface to create a protective barrier against the surrounding environment (Ahmed et al., 2020; Wang et al., 2023).

Corrosion inhibitors are compounds that effectively slow down the corrosion process when applied to corrosive media in a detectable concentration (Guo et al., 2023). These inhibitors lower the rate of corrosion by creating a protective layer on the material's surface, which forms a barrier between the material and the corrosive environment (Revie, 2008). Corrosion inhibitors significantly delay MS corrosion damage from exposure to acidic or alkaline environments and the resulting environmental pollution (Jawad et al., 2019). Depending on the kind of corrosion and the material being protected, there are two main types of corrosion inhibitors: inorganic and organic chemicals (Daoudi et al., 2023; Trentin et al., 2022; Ma et al., 2022). Each type has a unique mechanism of action and set of uses. Heteroatoms (such as N, S, or O) are found in the structures of organic inhibitors, which provide simple adsorption onto the metal's surface and form a protective film. Salts of metals such as phosphate, chromate, or zinc constitute the inorganic inhibitors. They form a passive layer on the metal surface by forming precipitate (Ma et al., 2022; Al-Amiery et al., 2023). Numerous organic inhibitors have been studied for their capacity to prevent corrosion; in their findings, some of the chemical compounds present in these inhibitors are amines, alcohols, and amino acids. According to Goyal et al. (2018), organic compounds including sulfur, nitrogen, and oxygen atoms erode more slowly because the metal's surface absorbed corrosion-stopping molecules. Chromate, silicate, phosphate, nitrate, and molybdate are examples of inorganic inhibitors.

Plant extracts are mixtures of different bioactive compounds isolated from plant tissues (such as leaves, bark, roots, fruits, flowers, seeds, or stems) through the use of suitable solvents (e.g., ethanol, water, acetone, methanol) and extraction techniques (Darbre, 2023). These extracts contain phytochemicals such as alkaloids, saponins, phenolics, terpenoids, flavonoids, and

tannins, which give them biological activities, antimicrobial, antioxidant, and corrosion-inhibitive properties (Garcia-Perez et al., 2016). Many plant extracts have been proven to be efficient corrosion inhibitors in environments containing H_2SO_4, HCl, NaOH, NaCl, H_3PO_4, etc. (Shwetta et al., 2024; Idu et al., 2023; Miralrio & Vazquez, 2020).

According to Gruca et al., 2015; Fern, 2014, the African fan palm (AFP), or *Borassus aethiopum,* is a single stemmed evergreen palm tree with massive fan-like leaves. AFP is a well-known and noticeable component of palm savannas in sub-Saharan Africa. It grows a big stem that is 80-85 cm in diameter and approximately 20-25 m tall. Orwa et al. (2009) notes that the crown of AFP may be up to 8m wide, and the bluish-green fan-like leaves including the petioles are up to approximately 3.5 m long.

Mild steel is a kind of carbon steel alloy with a comparatively low carbon content, usually between 0.05 and 0.25 percent by weight. Iron is the primary element in mild steel; however, it may also contain trace amounts of manganese, chromium, copper, aluminum, nickel, tin, lead, boron, vanadium, arsenic, sulfur, silicon, and phosphorus (Ebenso & Qurraishi, 2012). The low carbon content makes mild steel relatively soft, ductile, and easy to form, weld, and machine, compared to higher carbon steels. Mild steel is utilized in the engineering, manufacturing, and construction industries due to its low cost and considerable stability (Emmanuel, 2024). Many industrial food applications use mild steel, a very versatile ferrous alloy metal, due to its excellent mechanical properties, ease of fabrication, excellent welding ability, and low cost, which is six times lower than stainless steel (Balogun et al., 2022). This research evaluates the efficacy of silver nanoparticles synthesized from African Fan Palm (*Borassus aethiopum*) leaves in mild steel corrosion inhibition in an acidic medium (1 M HCl) using the weight loss analysis.

Problem Statement

The green synthesis of AgNPs has emerged as a promising alternative to conventional chemical methods due to its cost-effectiveness, environmental safety, and stability for biomedical and industrial applications. However, the utilization of *Borassus aethiopum dry leaf powder extract as a biogenic agent has not been adequately investigated. Current literature provides insufficient information on the optimal synthesis conditions required to obtain stable, uniformly distributed, and functional* AgNPs from this plant resource. This knowledge gap limits the scientific understanding and practical deployment of AFP-derived AgNPs in the real-world applications. Addressing this shortcomings is essential for improving nanoparticle performance and expanding their potential uses. To tackle this problem, the researcher used leaves of African Fan Palm (AFP)-based silver nanoparticles plant extracts, as anti-corrosive material to coat on MS in HCl medium through the mechanism of chemical adsorption to reduce corrosion and failure rate of MS.

Objectives of the Study

i. To synthesize AgNPs using AFP dry leaf powder as a natural reducing and stabilizing agent.

ii. To determine the functional groups of AFP extract that facilitate adsorption onto MS surface.
iii. To investigate the corrosion inhibition efficiency of the synthesized AgNPs on MS using weight loss analysis.
iv. To determine the corrosion rate from weight loss and surface coverage of the AFP-based nanoparticles plant extracts on MS.

Materials

The following materials were used to carry out the research study: dry leaves of AFP plant, silver nitrate ($AgNO_3$), magnetic stirrer, Centrifuge machine, Whatman filter paper, 1000 ml volumetric flask, spatula, 1M hydrochloric acid (HCl) (analytical grade), distilled water, analytical weighing balance, Mild steel sheets, Ethanol, acetone, ammonium acetate, Laboratory blender, test tubes, beakers, and a desiccator.

Methods

Preparation of AFP leaf extract

Fresh and healthy leaves were collected from mature AFP plants in the early morning hours, to ensure that the leaves were at their optimal physiological state. The leaves were manually cleaned to remove extraneous materials and washed thoroughly with tap water followed by distilled water to eliminate dust and other surface impurities. The cleaned leaves were air-dried under shade at ambient temperature for 14 days, as direct sunlight can degrade thermolabile phytochemicals (Sagar et al., 2024). The dried leaves were manually broken into smaller pieces using a spatula and ground into powder using a high-speed laboratory blender [Silver Crest (SC-1589)]. A stainless steel sieve of 425 µm mesh was used to sieve the leaf powder obtained. Aqueous extract was prepared by weighing 10 g of AFP leaf powder combined with 100 mL of distilled water in a 250 mL beaker and then heated at 70°C for 30 minutes with constant stirring using a magnetic stirrer. The extract was allowed to cool to room temperature and then filtered using Whatman filter paper No. 1 to remove solid residues. The filtered extract was then stored in a clean conical flask at 4°C.

Synthesis of Silver nanoparticles

The synthesis of silver nanoparticles (AgNPs) was done by dissolving 0.17 g of $AgNO_3$ in 1000 mL of distilled water to obtain 1 mM Silver nitrate solution. 10 mL the leaf extract was mixed with 90 mL of silver nitrate solution in a 250 mL beaker and stirred continuously using a magnetic stirrer at room temperature until the light yellow colour of the mixture completely changed into dark brown, which indicates AgNP formation. The silver nanoparticle colloid was centrifuged at 4,000 rpm for 40 minutes. The pellet was collected after discarding the supernatant. The pellet was washed with distilled water to remove excess ions and then recentrifuged. The pellet was then poured on a litmus paper and dried at room temperature. The process was repeated in multiples until the required quantity of AgNPs was obtained. The

resulting product was scraped using a spatula into a ceramic mortar and then pounded into fine powder. The dried AgNP powder was poured into a sterile, labelled bottle and then tightly sealed with aluminum foil. It was then stored in a dry, dark place until characterization.

Preparation of Coupons

Mild steel sheet was purchased from the metal market in Kaduna and mechanically cut into the required size using a CNC laser cutting machine (Bodor Thinker 3.0) to form different coupons in the mechanical workshop of Defence Industrial Cooperation of Nigeria (DICON), Kaduna, each of dimensions (3.0 x 2.0 x 0.1) cm with a tiny hole drilled at the edge for the purpose of suspension in the corrodant. The surfaces of the coupons were thoroughly polished to a mirror finish using sandpaper (emery paper grits of 320, 400, 600, 800, and 1000), degreased in acetone, and preserved in a desiccator. Subsequently, the initial weights (Wi) of the coupons were taken using a digital analytical weighing balance [Model: FA2104N, Serial No.: Y201212003, Production date: 8 (D) 12 (M) 2012 (Y)]. and then made ready for corrosion studies as adopted by Abu-Dalo et al., 2012; Egbeneje et al., 2023.

Reagent preparation

The stock concentrated HCl has density of 1.18 g/mL, concentration of 37% w/w, and molar mass of 36.46 g/mol. From the above data, each 100 g of acid solution contains 37 g of HCl. Volume of 100 g solution is given by:

$$V = \frac{100\ g}{1.18\ g/mL} = 84.76\ mL = 0.08476\ L$$

Number of moles of HCl is calculated as: $n = \frac{37\ g}{36.46\ g/mL} = 1.015\ mol$

From the above, the molarity of concentrated HCl was calculated to be 12 M (using $M = \frac{n}{V}$).

Using the dilution formula;

$$C_1V_1 = C_2V_2 \quad (1)$$

Where: $C_1 = 12$ M (stock HCl), $C_2 = 1$ M, $V_2 = 1000$ mL,

The calculated value of V_1 was 83 mL

Therefore, 83 mL of stock HCl was added to 500 mL of distilled water and then diluted to 1000 mL to obtain the desired 1 M HCl.

Inhibitor preparation

100 ppm of AFP AgNPs extract was prepared by dissolving 20 mg of the extract in 200 mL of 1 M HCl. Other higher concentrations were prepared using 30 mg, 40 mg, 50 mg, 60 mg, and 80 mg, respectively in the same volume of HCl.

Corrosion Studies

A blank sample was prepared for the study using 1M HCl, which was used as the control. Thereafter, the coupons were individually tied using non-reactive nylon thread through the tiny hole bored on the coupons and firmly held by a retort stand at an equal length, carefully avoiding any contact with the container walls or base. The coupons were completely immersed in the blank and corrosive medium with various concentrations (100, 150, 200, 250, 300, and 400 ppm) of prepared silver nanoparticles to ensure uniform exposure of all surfaces to the test solution. Full immersion was selected over partial immersion to eliminate edge effects and avoid differential aeration corrosion, thereby ensuring consistent and reproducible corrosion behavior. This set up facilitated free flow of the solution around the entire surface of the coupons and was performed at room temperature (30°C). After the time intervals (2, 4, 6, 12, and 24 hours), the coupons were removed and quenched in ammonium acetate, washed in distilled water, dried in acetone, kept in a desiccator, and then the final weights (Wf) were taken using the same balance under the same conditions as the initial weighing. The experiment was performed in duplicate.

Weight loss measurement

The method of Ostovari et al. (2009), Nnanna et al. (2014), and Elebo et al. (2024) was adopted, and weight loss was determined by the difference between the initial and the final weights of each test specimen, as shown in equation 2.

$$W_L = W_i - W_f \quad (2)$$

Where WL is the weight loss of the coupon, Wi is the initial weight, and Wf represents the weight after retrieval. Each reading reported is an average of two experimental readings recorded to the nearest 0.001 g. The inhibition efficiency (IE) was calculated using the formula represented by equation 3.

$$\% \text{ IE} = [1 - \frac{W_1}{W_2}] \text{ x } 100 \quad (3)$$

Where W_1 and W_2 are the weight losses in milligrams (mg) of the mild steel coupon in the presence and absence of the inhibitor, respectively, in the acid solution at the same temperature. The degree of surface coverage, θ, was evaluated using equation 4.

$$\theta = 1 - \frac{W_1}{W_2} \quad (4)$$

The corrosion rate of the mild steel coupons was determined for the immersion period from weight loss using equations 5 and 6

$$C_R \text{ (mg/cm}^2\text{h}^{-1}) = \frac{W_L}{\text{At}} \quad (5)$$

Where, W_L is the weight loss in milligrams (mg), A is the coupon surface area in cm^2 and t is the immersion time in hours (Abu-Dalo et al., 2012).

Shwetta et al. (2024) reported that Corrosion rate could also be expressed in mm/yr using equation 6

$$C_R \text{ (mm/yr)} = \frac{87.6\, W_L}{DAt} \quad (6)$$

Where; W_L is the weight loss in milligrams (mg)
D is the density of mild steel (7.85 gcm^{-3})
A is the coupon's exposed area in cm^2.
t is the immersion time in hours.

Results and Discussion

Determination of composition of mild steel coupon

An Energy Dispersive X-ray Spectroscopy (SPECTROMAX) machine with model (MAXx LMF14), dated 27.03.2009, and S/N: 09001204 was used to determine the mild steel composition. Table 1 gives the elemental constituents of the mild steel samples used for this research.

Table 1: Composition of mild steel coupon

Elements	Composition (%)
C	0.1300
Si	0.1330
Mn	0.5500
P	<0.0000
S	<0.0000
Cr	0.0300
Ni	0.0360
Mo	0.0110
Al	0.0030
Cu	0.5000
Co	0.0180
Ti	0.0092
Nb	0.0270
V	<0.0000
W	0.1390
Pb	0.0510
Mg	0.0260

B	<0.0000
Sn	0.0096
Zn	>0.1560
As	0.0061
Bi	0.0034
Ca	0.0003
Ce	0.0280
Zr	<0.0000
La	0.0640
Fe	<98.1000

FTIR Analysis

The FTIR analysis was carried out using SHIMADZU FTIR-8400S Fourier Transform Infrared Spectrophotometer. The result is shown in figure 1.

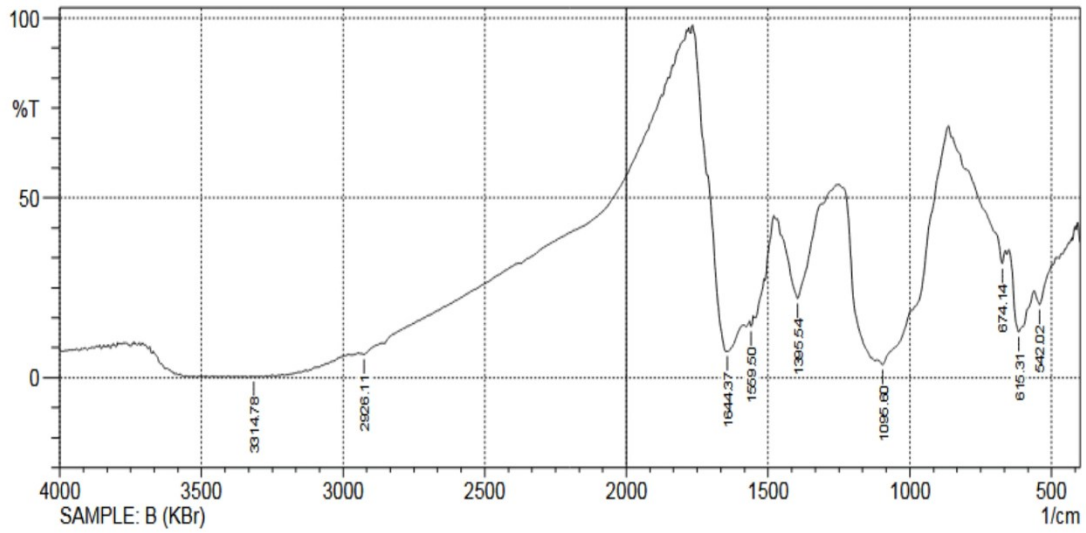


Figure 1: FTIR spectral analysis

The FTIR spectrum of the synthesized AgNPs exhibited absorption bands at ≈3315, 2926, 1644, 1560, 1396, 1096, 674, 615, and 542 cm^{-1}. The broad O-H, N-H stretching band at 3315 cm^{-1} and the C-O stretching band at 1096 cm^{-1} indicate the presence of phenolic and polyol compounds responsible for the reduction of Ag^{+} ions to Ag^{0}. Bands at 1644 cm^{-1} [amide I (C=O)] and 1560 cm^{-1} (amide II) confirm the involvement of proteins in nanoparticle capping and stabilization. The peak at 1396 cm^{-1} corresponds to carboxylate vibrations, suggesting the binding of carboxyl-containing phytochemicals to the silver surface. Notably, the low-

frequency band at 542 cm^{-1} corresponds to metal-oxygen (Ag-O) stretching, validating the formation of silver-biomolecule complexes (FTIR, 2025). These results confirm that phytoconstituents in the AFP extract served as both reducing and stabilizing agents in the green synthesis of AgNPs.

UV-Visible Analysis

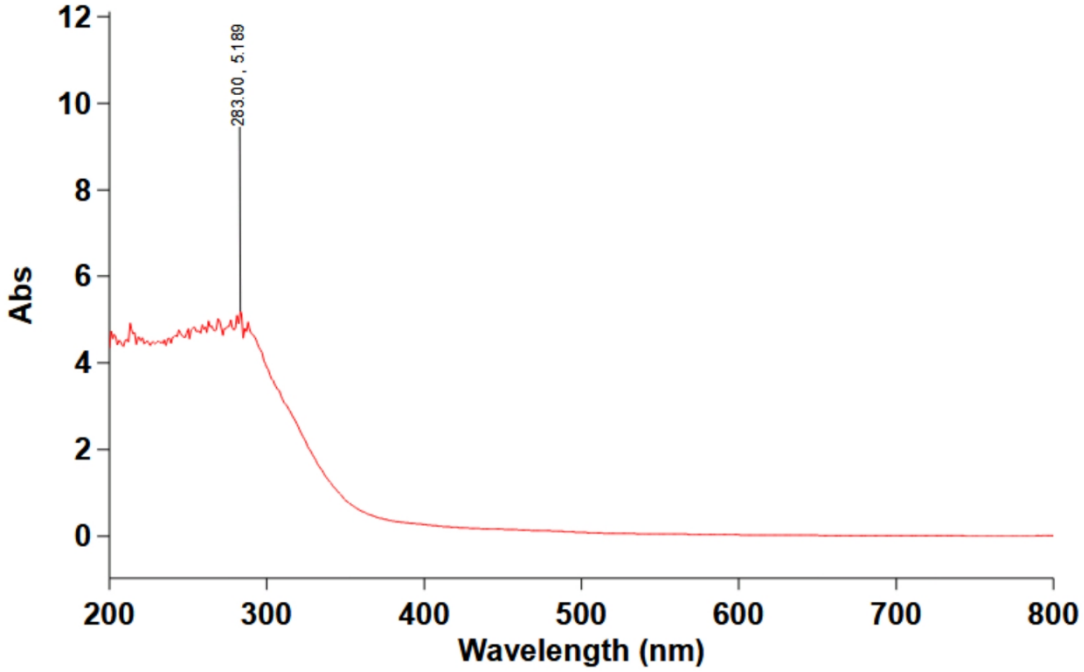


Figure 2: UV-Vis spectral analysis

The UV-Vis spectrum of the synthesized silver nanoparticles exhibited a single strong absorption peak at 283 nm, as shown in figure 2, corresponding to the surface plasmon resonance (SPR) band of the AgNPs. The occurrence of this distinct peak is a clear indication of nanoparticle formation, as the SPR band arises from the collective electrons in response to the light excitation. The observed blue-shifted SPR relative to the typical AgNP absorption range of 400-450 nm may suggest the formation of ultrafine nanoparticles (10 nm) with strong surface interactions. This shift may be attributed to intense capping by biomolecules from the AFP extract. The absence of additional peaks in the 500-800 nm region indicates a monodisperse, non-aggregated, and spherical nanoparticle population. The high absorbance intensity (A = 5.189) indicates a concentrated nanoparticle suspension.

This observation reflects a uniform nucleation process facilitated by phytochemicals acting as both reducing and stabilizing agents during biosynthesis. The interaction between silver atoms and functional groups such as –OH, -NH, and C=O as identified by the FT-IR analysis may be responsible for the shift in the SPR band towards shorter wavelengths. The presence of a

strong capping layer (amide + carboxylate) typically explains the narrow, stable SPR peak near 420 nm, as shown in Figure 2.

Weight loss Analysis

Table 2 - 6 represents the Percentage inhibition efficiency for AgNP extract concentrations for different exposure times (2, 4, 6, 12, and 24 hours) as obtained from the weight loss analysis.

Table 2: Percentage inhibition efficiency for AgNPs extract concentrations in 2 hours

Inhibitor Concentration (ppm)	Inhibition Efficiency (I E) %
100	33.3
150	46.7
200	53.3
250	60.0
300	66.7
400	73.3

Table 3: Percentage inhibition efficiency for AgNPs extract concentrations in 4 hours

Inhibitor Concentration (ppm)	Inhibition Efficiency (I E) %
100	28.6
150	50.0
200	57.1
250	60.7
300	64.3
400	75.0

Table 4: Percentage inhibition efficiency for AgNPs extract concentrations in 6 hours

Inhibitor Concentration (ppm)	Inhibition Efficiency (I E) %
100	22.2
150	37.8
200	42.2
250	51.1
300	60.0
400	68.9

Table 5: Percentage inhibition efficiency for AgNPs extract concentrations in 12 hours

Inhibitor Concentration (ppm)	Inhibition Efficiency (I E) %
100	17.7
150	33.3
200	48.9
250	63.3
300	70.0

400	75.6

Table 6: Percentage inhibition efficiency for AgNPs extract concentrations in 24 hours

Inhibitor Concentration (ppm)	Inhibition Efficiency (I E) %
100	34.2
150	48.4
200	49.7
250	53.5
300	72.3
400	80.6

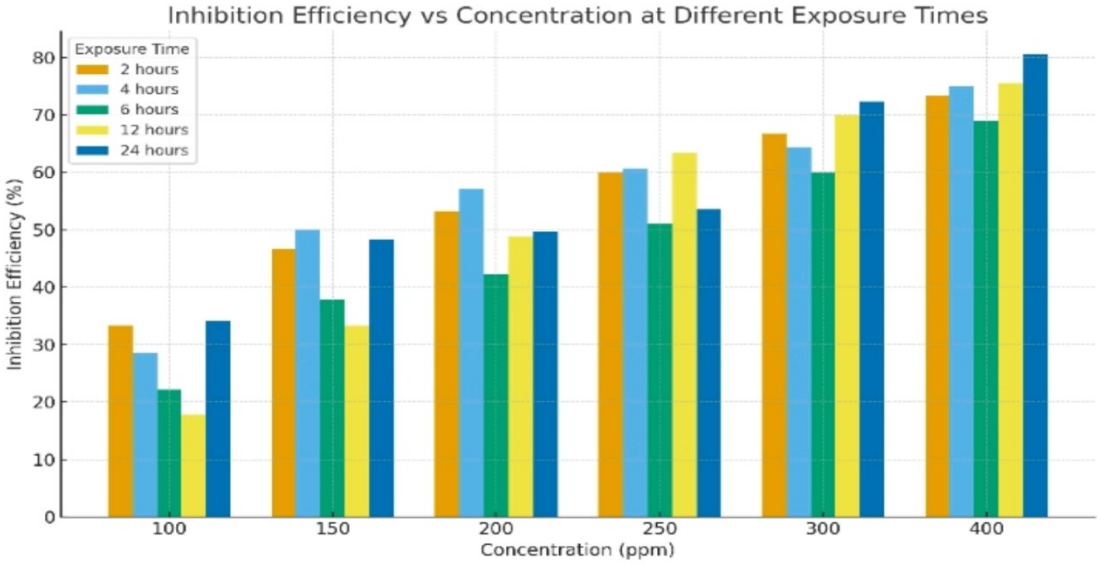


Figure 3: Inhibition efficiency versus Inhibitor concentration at different exposure times

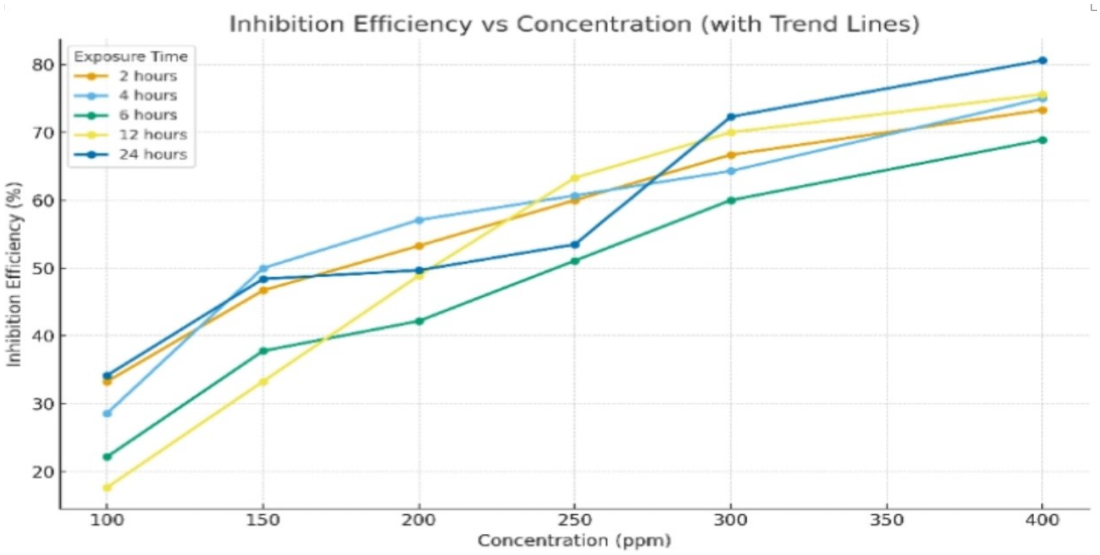


Figure 4: Trend lines of Inhibition efficiency versus Inhibitor concentration at different exposure times

Conclusion

This study successfully established the green synthesis of AgNPs using AFP dry leaf extract, confirming the extract's phytochemicals as effective natural reducing and stabilizing agents. Spectroscopic analysis verified nanoparticle formation with blue shift and stability, with the surface plasmon resonance at 283 nm, while the FTIR spectrum confirmed the involvement of biomolecules in both silver ion reduction and the capping process. Corrosion inhibition studies on mild steel demonstrated that corrosion inhibition efficiency increased with increase in inhibitor concentration, attaining a maximum of 80.6% and surface coverage of ≈ 0.81 at 400 ppm after 24 hours of immersion. The minimum corrosion rate of 0.208 mg/cm²/h⁻¹ (2.32 mm/yr) was obtained at the same concentration. The increase in inhibitor concentration from AFP AgNPs yielding an increase in corrosion inhibition efficiency is in agreement with the reports of Udoisoh et al., 2024; Egbeneje et al., 2023; and Abu-Dalo et al., 2012.

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