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Eco-Friendly Corrosion Mitigation of AISI 1020 Steel in Alkaline Media Using Arachis Hypogaea Shell Extract: Concentration and Immersion Time Effects

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ABSTRACT

Corrosion is a major factor limiting the service life of carbon steel, particularly in alkaline environments encountered in industries such as oil and gas. The objective of this study is to evaluate Arachis hypogaea (groundnut) shell extract as a sustainable corrosion inhibitor for AISI 1020 steel in alkaline media. The inhibitor was prepared via Soxhlet extraction and rotary evaporation and characterized using Fourier Transform Infrared (FTIR) spectroscopy. Corrosion performance was assessed using weight loss measurements, macrostructural and microstructural observations, and Rockwell hardness testing. Experiments were conducted at inhibitor concentrations of 10%, 20%, and 30% v/v, with immersion periods of 7, 14, and 21 days. Results revealed a clear correlation between inhibitor concentration, immersion time, and corrosion resistance. Increasing the inhibitor concentration markedly reduced the corrosion rate, achieving a maximum inhibition efficiency of 97.331% at 30% after 7 days. Prolonged immersion maintained superior protection compared to uninhibited control, indicating sustained inhibitor activity. Additionally, samples immersed with the presence of Arachis hypogea shell extract revealed improved hardness values, suggesting enhanced mechanical performance alongside corrosion resistance. The findings confirm the potential of Arachis hypogaea shell extract as an eco-friendly, cost-effective corrosion mitigation approach for carbon steel in alkaline environments, offering benefits in both protection and mechanical durability.

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INTRODUCTION

Corrosion remains one of the most significant challenges affecting the performance and longevity of carbon steel, particularly in chemically aggressive environments such as oil and gas pipelines, boilers, offshore platforms, and structural systems. As carbon steel accounts for over 50% of global steel usage, its susceptibility to electrochemical degradation poses major economic, safety, and structural concerns. Corrosion results in severe surface damage, structural failures, loss of mechanical integrity, reduced flexural strength, dimensional instability, and impaired interfacial adhesion, ultimately shortening service life and increasing maintenance cost (Damborenea, 2014). Conventional corrosion control strategies include alloy modification, impurity reduction, cathodic protection, metal plating, surface treatments, and protective coatings (Wang et al., 2023; Hu et al., 2022; Park et al., 2023). Among these, corrosion inhibitors have emerged as a cost-effective and practical approach, especially for alkaline environments. These chemicals act primarily by adsorbing onto the metal surface, forming a passivating film that limits interaction with corrosive agents (Chigondo & Chigondo, 2016). However, most commercial inhibitors are synthetic and often contain toxic substances, posing risks to human health, aquatic systems, and environmental stability (Rittihong et al., 2023).

In response to these concerns, research on green corrosion inhibitors derived from renewable, biodegradable, and non-toxic sources has intensified to reduce environmental and human health impacts. Many researchers have come up with ideas to study plants, flowers, leaves, fruit, and peel as natural resources to replace the existing chemical inhibitors (Kumar & Das, 2024; Fajobi & Loto, 2022a; Pal & Das, 2022; Omotioma & Onukwuli, 2016; Abd El-Nabey et al., 2024). Plant-derived inhibitors, containing active heteroatoms such as N, O, S, and P, as well as phytochemicals like tannins, alkaloids, flavonoids, and saponins, are known to disrupt anodic or cathodic reactions, thereby reducing corrosion rates (Kandikonda et al., 2022; Olawale et al., 2018; Ali et al., 2024). Several plant parts, including husks, leaves, roots, peels, and oils, have been reported to achieve inhibition efficiencies above 80% (Golshani et al., 2023; Wazzan, 2023), with performance generally improving with increasing inhibitor concentration (Ouknin et al., 2023; Kaya et al., 2023). Notable examples include Tinospora cordifolia extract with high efficiency against mild steel corrosion (Hussin et al., 2016) and acerola aqueous extract achieving up to 96% inhibition over extended immersion (Paiva et al., 2024). Additionally, agricultural wastes such as rice straw (Oyewole et al., 2022) and olive leaves (Elhady et al., 2023) have shown promising results, demonstrating the dual benefits of corrosion control and waste valorization.

Groundnut (Arachis hypogaea) products have also shown significant corrosion inhibition potential due to their phytochemical composition, including saponins, glycosides, alkaloids, terpenoids, quinones, and steroids, which promote protective film formation (Abdulwahab et al., 2012; Olawale et al., 2018). Groundnut oil and leaf extracts have achieved efficiencies up to 86.3% in acidic media (Fajobi & Loto, 2022b), yet limited research exists on the application of groundnut hull waste for corrosion protection. Given the abundance of this agricultural byproduct, its utilization not only offers a sustainable corrosion mitigation strategy for AISI 1020 steel in alkaline environments but also contributes to environmental sustainability by transforming waste into a valuable industrial resource. The objective of this research is to investigate novel corrosion inhibitors derived from Arachis Hypogaea shell extract, with the aim of reducing corrosion incidence while ensuring lower toxicity.

METHODS AND MATERIAL

The experimental procedures employed in this study were conducted in accordance with the methodology illustrated in Fig 1. This schematic outlines the sequence of steps followed, including sample preparation,

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inhibitor extraction process, immersion conditions, and analysis techniques. All materials, reagents, and instruments used were selected to ensure consistency and reproducibility throughout the study.

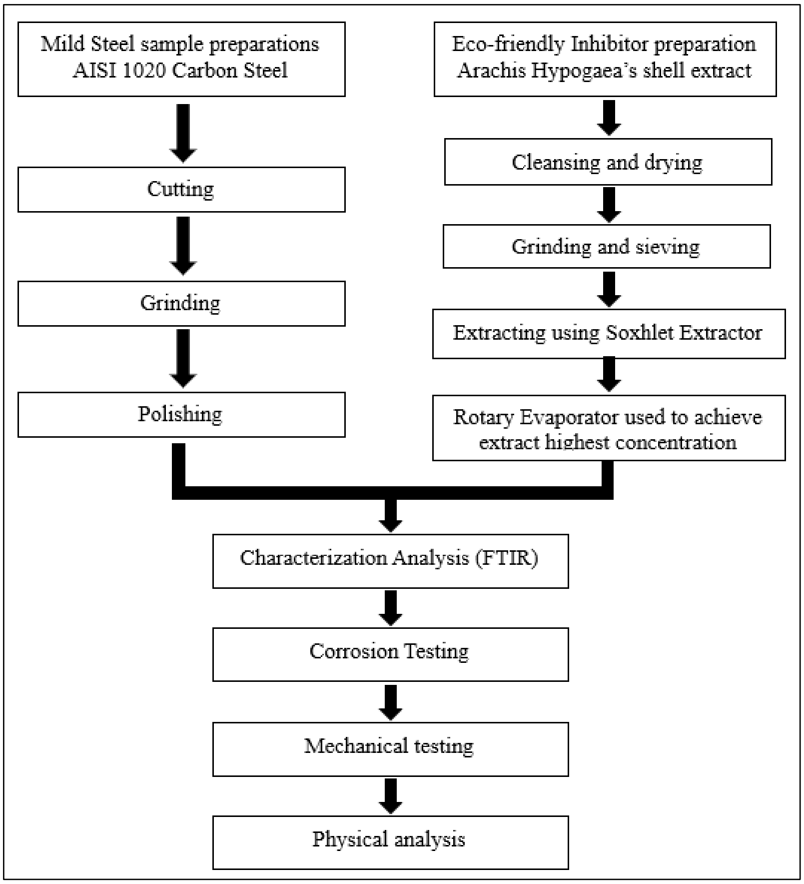

Fig. 1. Illustration of the materials and method used.

Preparation procedure for AISI 1020 steel samples

Preparation of the AISI 1020 steel samples began by cutting the material into dimensions of 50 × 25 × 3 mm using an abrasive cutter. Once sectioned, the samples were ground using successive grades of sandpaper to produce a smooth, uniform surface finishing, reaching up to 1200 grit. This grinding step served to eliminate any surface flaws or irregularities. Afterward, polishing was carried out using diamond suspensions with particle sizes of 3 µm and 1 µm, progressively refining the surface to achieve a mirror-like appearance and remove any residual defects. To ensure the removal of contaminants or residues introduced during preparation, the polished specimens were rinsed with acetone. Hot air drying followed, ensuring the complete evaporation of any remaining solvent or moisture. The entire surface preparation process was strictly followed by the ASTM G31-72 standard, which guarantees surface consistency and integrity, both critical for reliable evaluation of corrosion behavior and related properties. The chemical configuration of the prepared samples was determined using a spectrometer. The analysis yielded the following elemental percentages: 0.316% Carbon, 0.168% Silicon, 0.56% Manganese, 0.022% Phosphorus, 0.012% Sulfur, 0.193% Chromium, 0.081% Nickel, 0.0228% Copper, with the balance being Iron (Fe). These values fall within the standard compositional range specified for AISI 1020 steel.

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Plant-based inhibitor extraction method

The cleansing process began by thoroughly washing the Arachis hypogaea shell waste with distilled water, effectively removing unwanted impurities and surface contaminants. Subsequently, the waste was dried under controlled heat at 80 °C for approximately two hours to dislodge moisture. The dried material was then grounded and milled to achieve a particle size of up to 35 mesh. The resulting powder undergoes an extraction processed by dispersing it into 70% pure Ethanol using a Soxhlet Extractor. Different weight percentages of Arachis Hypogaea (10%, 20%, and 30%) were mixed with 200 ml of Ethanol for a minimum of 6 hours. 10% was chosen as the initial weight percentage to ensure the purity of the extraction could be achieved for the solution to retard the process of corrosion. The Rotary Evaporator was employed at 75 °C to obtain the Arachis Hypogaea highest concentrated solution. The standard of procedure for the soxhlet extraction process is in accordance with EPA 3540C – Standard Test for the Soxhlet Extraction Process.

Arachis hypogaea's extract characterization

The extract of Arachis hypogaea was characterized using Fourier Transform Infrared Spectroscopy (FTIR) to identify functional groups and detect the presence of heteroatoms, which are the key indicators of corrosion inhibition potential. FTIR analysis was carried out over the spectral range of 4000 cm^{-1} to 500 cm^{-1} using a VERTEX 70 spectrometer to determine the characteristic absorption bands associated with the active functional groups responsible for the inhibitor's effectiveness.

Corrosion resistance testing

The corrosion behavior of AISI 1020 steel was systematically evaluated in an alkaline medium using a 1 M NaCl solution. Corrosion rates were determined through the gravimetric (weight loss) method. For each immersion duration, 7, 14, and 21 days, four steel coupons were prepared, and the weight of each sample was examined before and after being immersed in Arachis hypogaea shell extract. To investigate the long-term stability and effectiveness of the inhibitor, immersion time was treated as a critical variable. The study assessed inhibitor performance over extended exposure periods, following the guidelines established by ASTM G31 (Standard Guide for Laboratory Immersion Corrosion Testing of Metals) (Faustin et al., 2015). The inhibitory efficacy of the extract was tested at four concentration levels: 0% (blank), 10%, 20%, and 30% (v/v). Each set of tests was conducted at room temperature, and corrosion rates were calculated based on the mass loss of the steel samples after the specified immersion periods. This method simulates the inhibitor's performance under prolonged exposure in corrosive alkaline environments.

Analysis of metal loss, corrosion kinetics, and inhibitor performance

Weight loss measurements were carried out by fully immersing AISI 1020 carbon steel samples in 250 ml beakers containing 1 M sodium chloride (NaCl) solution. Each specimen was weighed prior to immersion and then placed into the solution for defined exposure durations of 7, 14, and 21 days. After the specified immersion periods, the samples were carefully removed and cleaned to eliminate corrosion products. This cleaning process involved a gentle wipe using dry and clean cloth, followed by rinsing with distilled water and cleaning with acetone to ensure the removal of any residual moisture or contaminants. The mass of each sample was recorded again after drying. Weight loss was calculated by comparing the pre- and post-immersion weights. Corrosion rates, expressed in millimeters per year (mm/y), were then computed using Equation 1, which relates the weight loss to the surface area, immersion time, and density of the material.

$$CR = \frac{K \times w}{A \times t \times \rho} \tag{1}$$

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Here, K is a constant (unit conversion factor) that adjusts the result to millimeters per year. While w represents the weight loss (g) of the specimen after an exposure time t (hours). A is the surface area of the specimen (mm²), and ρ is the density of the steel (g/cm³). These parameters are used to calculate the corrosion rate (CR) for each exposure period. The inhibition efficiency is then determined using the following Equation 2.

$$IE\ \% = \frac{w_0 - w_1}{w_0} \times 100 \qquad (2)$$

where w_1 and w_0 represent the weight loss of the specimen in the presence and absence of the inhibitor, respectively, and *IE%* denotes the inhibition efficiency.

Mechanical hardness testing

Following completion of both the weight loss and corrosion tests, the samples were advanced to the next phase involving mechanical testing. All samples were further examined to evaluate the sample's hardness capability before and after exposure to corrosive environments, utilizing a Rockwell hardness testing machine. Subsequently, the average of these 10 readings was taken as the representation of the overall hardness of each AISI 1020 steel sample (Ikechukwu & Pauline, 2015). The test was conducted according to the ASTM E18 standard test method.

Macrostructure and microstructure analysis

After immersion, a comprehensive visual examination of the materials was performed to detect any observable alterations or corrosion effects. The surface of all the sample steels was analyzed after immersion in corrosive media for durations of 7 to 21 days, both with and without the addition of a corrosion inhibitor. The image acquisition was performed using the micro mode of a 50 MP ZEISS OIS Autofocus Camera equipped with Bionic Spectrum technology. Macrostructural analysis examines larger, easily visible features of materials, usually at a scale that can be seen with the naked eye or using low magnification tools like optical microscopes. When assessing the effectiveness of a corrosion inhibitor for steel, this type of analysis is crucial as it provides a broad perspective on how corrosion impacts the material.

All immersed specimens were subjected to surface characterization using an optical microscope (Xoptron X80 series) to evaluate the extent of microstructural modifications resulting from the corrosion process. This analysis was conducted to compare morphological changes among samples exposed to different immersion durations and various concentrations of corrosion inhibitors. The use of a uniform magnification level of 50× ensured consistent visual scaling, allowing for reliable comparative assessment of corrosion damage and protective film formation across all test conditions. Optical microscopy was selected for this stage of analysis due to its effectiveness in revealing grain structures, surface etching patterns, and inhibitor-induced surface films, which are critical for understanding the corrosion inhibition mechanism.

RESULTS AND DISCUSSION

Fourier transform infrared (FTIR) analysis

The synthesized Arachis hypogaea extract was characterized using FTIR spectroscopy to identify its molecular configuration and functional moieties. As shown in Fig 1, the FTIR spectra provide valuable information on the extract's chemical composition. All procedures adhered to the guidelines outlined in

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ASTM E1232-98. Functional groups and heteroatoms present in the extract play a critical role in corrosion inhibition, as they significantly affect the way the inhibitor species engage with the metallic substrate.

The peaks observed in the FTIR spectra depicted in Fig 2, were attributed to several groups and bands based on their corresponding wave numbers (cm^{-1}), indicating the intricate composition of the adsorbent. The wide spectral range centered at 3388 cm^{-1} is ascribed to the surface hydroxyl groups (-OH), which are likely a result of the interaction and existence of alcoholic, phenolic, amino, and carboxylic. The peaks at 1629.74 cm^{-1} show results from C=C stretching, suggesting the presence of aromatic compounds or alkenes, which are common in plant phenolics. C-H stretching vibration shown at peak 2920 cm^{-1} indicated the functional group presence in aliphatic hydrocarbons, also commonly found in plant extracts. The absorption peaks observed at 1407 cm^{-1} and 1271 cm^{-1} may be attributed to stretching vibrations of C─O, C─H, or C─C bonds. The 1051 cm^{-1} peak is attributed to the C─O functional group present in carboxylic and alcoholic groups. The intensity of the C─O group's band in Fig 2 surpassed that of the C=O group, potentially because there are more C─O groups present in groundnut shells. The presence of the peak at 588 cm^{-1} may be attributed to the vibrational bending occurring in the aromatic chemicals found in lignin (Prasad et al., 2022).

The FTIR spectra, presented in the figure, expose the occurrence of diverse functional groups and heteroatoms in the Arachis hypogaea extract. These chemical constituents are thought to strongly facilitate the chemisorption of inhibitors onto the steel surface. Through these surface interactions, the extract enhances its ability to reduce corrosion by forming a protective molecular barrier.

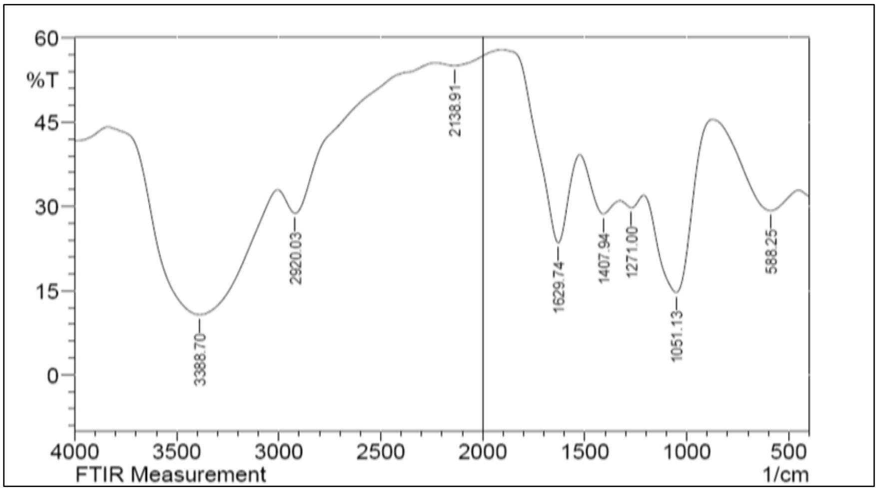

Fig. 2. Arachis hypogaea FTIR spectroscopy results.

Corrosion rate and inhibiting efficiency

The corrosion behavior and protective efficiencies of AISI 1020 steel in alkaline conditions are represented in Fig 3. The figure demonstrates how immersion duration and varying concentrations of the corrosion inhibitor influence the corrosion behavior over time. The data presented in the figure indicates that, in the absence of a corrosion inhibitor, AISI 1020 steel exhibited an average corrosion rate of 0.02910 mm/y when immersed for 7 days in the alkaline medium. The introduction of a 10% concentration of the Arachis hypogaea extract significantly reduced the corrosion rate to 0.00300 mm/y, corresponding to an inhibition efficiency of approximately 89.706%. Further increases in inhibitor concentration to 20% and 30% resulted in additional reductions in the corrosion rate to 0.00260 mm/y and 0.00130 mm/y, respectively. These findings demonstrate a clear trend: increasing the inhibitor concentration enhances the

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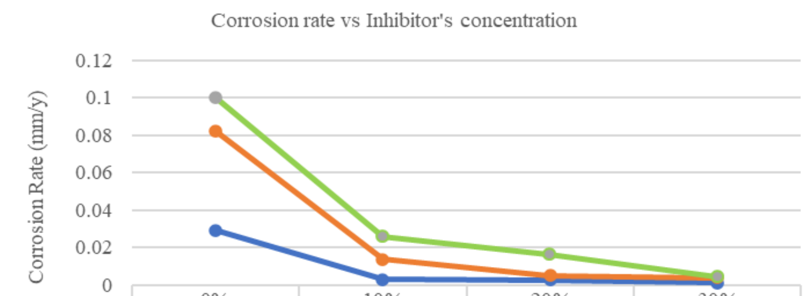
protective effect, although the rate of improvement begins to plateau. Specifically, the difference in corrosion rate between 20% and 30% concentrations was relatively small, about 4.12%, indicating diminishing returns at higher concentrations.

Corrosion resistance was adversely affected by the extension of immersion time. When the exposure period escalated over the 7 to 14 day interval, the corrosion rate rose sharply to 0.0825 mm/y, showing a significant increase of approximately 183.51%. This trend continued for 21 days, with corrosion rates further escalating to 0.1002 mm/y. The results suggest that extended contact with the corrosive alkaline medium accelerated the degradation process, potentially due to the depletion of the inhibitor over time or changes in surface chemistry. Nevertheless, as the inhibitor's concentration increased from 10% to 20% and 30% over the 14-day and 21-day immersion periods, a significant reduction in corrosion rate was observed. Although a general increase in corrosion progression was expected on day 14 and day 21, the application of the inhibitor effectively mitigated the severity. For instance, the corrosion rate of 0.1002 mm/year recorded on day 21 in the uninhibited condition was reduced to 0.0257 mm/year with the introduction of 10% inhibitor. This reduction became more pronounced with the use of 20% with corrosion rates of 0.0161 mm/y and 0.0045 mm/y at 30% inhibitor concentrations, demonstrating enhanced protective performance of 72.05% at higher dosages. The study confirms that increasing the volume fraction of the Arachis Hypogaea's husk extract effectively reduces corrosion rates, especially at earlier immersion periods. However, extended immersion durations reduce this protective effect, underscoring the importance of optimizing both inhibitor concentration and exposure time to ensure sustained corrosion protection.



	0%	10%	20%	30%
7 days	0.0291	0.003	0.0026	0.0013
14 day	0.0825	0.0138	0.0051	0.0039
21 days	0.1002	0.0257	0.0161	0.0045

Fig. 3. Corrosion rate AISI 1020 steel exposed to alkaline sodium chloride solution.

Fig 4 highlights how the inhibition efficiency of AISI 1020 carbon steel is influenced by different concentrations of corrosion inhibitors over time. A clear trend emerges: the higher the inhibitor concentration, the greater the protection offered. This can be explained by the increased adsorption of active compounds from the extract onto the steel surface, which enhances the formation of a stable protective barrier. Among the samples tested, the lowest inhibition efficiency was 74.359%, observed after 21 days of immersion in NaCl with a 10% inhibitor concentration. In contrast, the highest efficiency reached 95.588%, recorded at a 30% concentration after just 7 days of exposure. The drop in efficiency over time, especially at lower concentrations, may result from gradual degradation or detachment of the inhibitor film, which becomes less effective under prolonged contact with the corrosive medium. At lower doses, the inhibitor may also be insufficient to maintain full surface coverage, allowing more corrosive species to

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reach and interact with the metal. These combined factors reduce the long-term protection offered by the extract.

The findings of this study reaffirm the potential of Arachis hypogaea extract as an environmentally friendly corrosion inhibitor for carbon steel. Comparable behavior in alkaline media was reported by Baitule & Manivannan (2025) when employing Azadirachta indica (neem) extract in an alkaline medium, thereby aligning closely with the inhibition performance observed for Arachis hypogaea shell's extract in the present work.

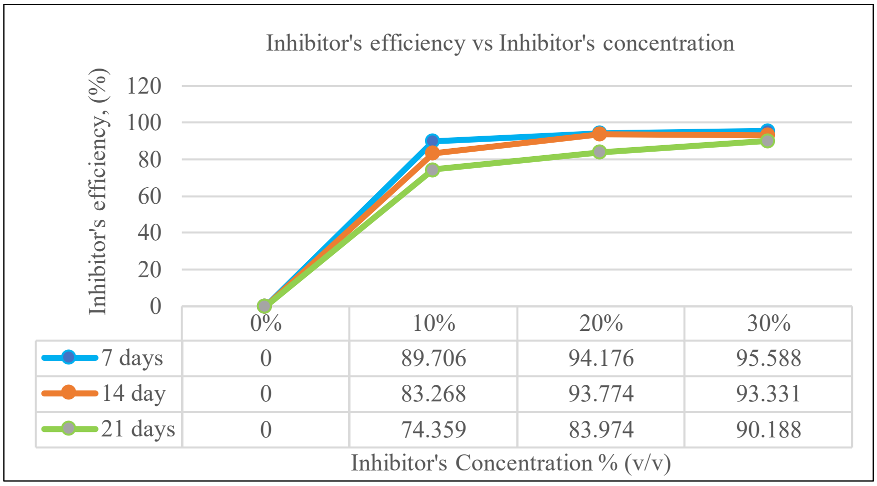

Fig. 4. Inhibition efficiency of AISI 1020 steel exposed to alkaline sodium chloride solution.

In the absence of Arachis hypogaea extract, AISI 1020 carbon steel exposed to the alkaline environment exhibited severe surface degradation, as evidenced in Fig 5(a), confirming the lack of protective action and the accelerated corrosion rate. The encouraging results obtained from the inhibition tests suggest that Arachis hypogaea extract has good potential to act as a protective agent for AISI 1020 carbon steel in alkaline conditions, as shown in Fig 5(b). The extract appears to function by attaching itself to the steel surface, where it forms a thin, adherent layer that helps to reduce direct contact between the metal and the corrosive solution. This protective layer slows down the movement of aggressive ions, particularly hydrogen and chloride, towards the AISI 1020 surface, thereby lowering the rate at which corrosion occurs. The effectiveness of this process is likely due to the natural compounds present in the extract, which contain functional groups capable of interacting with steel. Over time, this interaction helps to stabilize the surface and preserve the integrity of the metal.

Surface hardness assessment

The investigation involved the evaluation of hardness changes in AISI 1020 carbon steel samples. The corrosion assessment was conducted on four samples, succeeded by subsequent Rockwell Hardness examinations. Each sample was subjected to immersion periods extended over 7 to 21 days, and a range of inhibitor concentrations from 0% to 30% was applied within an alkaline medium. The main objective was to examine how varying inhibitor concentrations affect the mechanical strength of the steel specimens. Fig 6 presents the Rockwell hardness measurements of all samples over extended immersion periods.

The obtained outcomes presented a subtle trend in the Rockwell hardness behavior of the steel samples in response to varying inhibitor concentrations. The influence of inhibitor concentration on the hardness of AISI 1020 carbon steel was evaluated over different immersion periods. After 7 days, increasing the

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inhibitor concentration from 0% to 30% led to a modest increase in hardness of approximately 4.6%. However, as immersion time increased, the effect became more distinct. After 14 days and 21 days, the hardness increase reached 10.19% and 21.48%, respectively. This increasing enhancement suggests that prolonged exposure to higher concentrations of the corrosion inhibitor not only offers protective benefits against corrosion but also contributes positively to the surface hardness of the steel over time. Similar findings have been reported in previous studies, where the formation of protective inhibitor-derived surface films led to changes in surface composition and hardness due to barrier effects and interactions at the metal–inhibitor edge (Eddy & Ebenso, 2010). The graphical representation of the hardness results is presented in Fig 6, immersed in the alkaline medium. These graphic representations offer a comprehensive platform for contrasting the hardness measurements across various inhibitor concentrations and immersion durations.

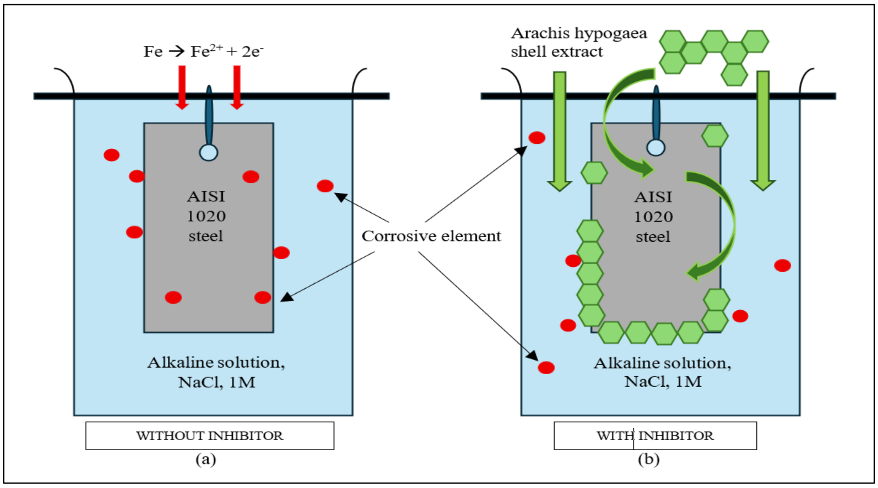

Fig. 5. Corrosion inhibition mechanism of AISI 1020 steel in alkaline medium with and without AH extract.

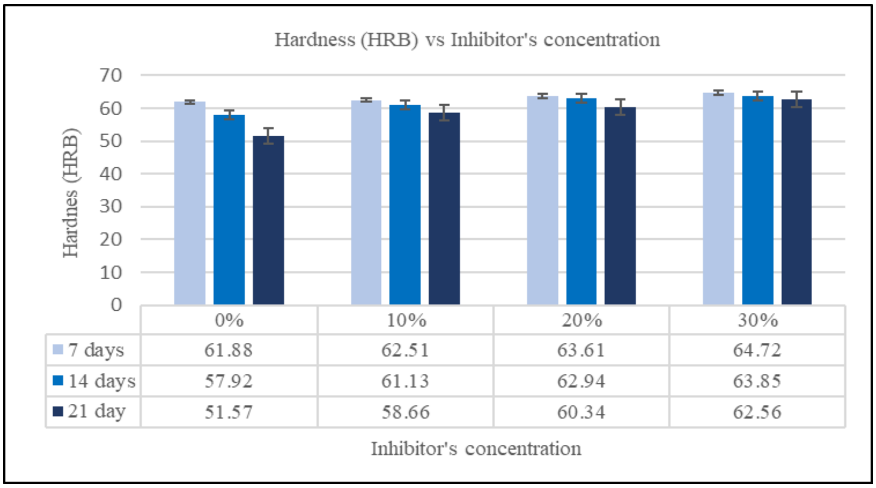

Fig. 6. Hardness value for samples in alkaline (NaCl) medium.

The findings underscore the constructive correlation between increased inhibitor concentrations and enhanced hardness attributes in AISI 1020 carbon steel samples. Nevertheless, the extended immersion

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duration contributed to a reduction in hardness, underscoring the importance of carefully determining the optimal exposure time frame to uphold desirable hardness properties when corrosion inhibitors are introduced.

Macrostructural evaluation

Table 1 provides a comprehensive overview of the macroscopic structure of AISI 1020 steel under various conditions. When submerged in a sodium chloride (NaCl) solution with varying corrosion inhibitor concentrations, the sample surface did not exhibit any notable morphological changes; however, initial signs of corrosion became apparent, such as a dark grey appearance, as the immersion period progressed from 7 to 21 days, particularly in steel samples immersed in the alkaline solution without the presence of any corrosion inhibitor. As the concentration of the corrosion inhibitor increased, a visible reduction in corrosion severity was observed. This was evidenced by the color transition on the steel surface from a darker color to lighter grey and eventually to a silvery appearance, indicating diminished corrosion activity and the development of a more effective shielding layer. The inhibitor's performance in shielding the steel surface became more apparent at higher concentrations.

In contrast, extending the immersion period to 21 days led to greater exposure to the underlying metal, revealing the continued progression of corrosion over time. Despite this, samples treated with elevated inhibitor concentrations showed significantly better surface preservation. This protective effect was visually confirmed through surface imaging, where treated samples appeared cleaner and exhibited fewer signs of corrosion or surface defects. Meanwhile, untreated samples experienced noticeable surface degradation, especially after prolonged immersion. These observations suggest that increasing the inhibitor dosage improves surface protection by enabling the formation of a more stable and uniform adsorption layer, which effectively reduces the interaction between the steel and the corrosive alkaline environment. In conclusion, the results clearly demonstrate the efficiency of Arachis hypogaea-based corrosion inhibitors in protecting AISI 1020 steel. Higher concentrations yielded better corrosion resistance, underscoring the potential of these green inhibitors in enhancing surface integrity and minimizing degradation.

Microstructural evaluation

Microscopic examination of the steel specimens revealed clear differences in surface morphology, strongly influenced by both immersion time and the concentration of AHHE inhibitor. Without any inhibitor (0% AHHE, 21 days), the steel surface showed severe deterioration, including pronounced surface roughness and visible material loss. These effects were most evident along grain boundaries, which appeared as sharply etched lines under optical microscopy. Extended exposure allowed these boundaries to act as preferential paths for localized dissolution, eventually leading to cavity formation and a weakened microstructure. The uninhibited steel also displayed a coarse-grained structure, and the absence of a protective film allowed the alkaline medium to penetrate deeply into intergranular regions. As immersion time increased from 7 to 21 days, surface damage became progressively more severe, confirming a strong time-dependent deterioration in the absence of protection.

When AHHE was introduced at concentrations of 10%, 20%, and 30%, the corrosion response changed noticeably. Compared to the uninhibited sample, inhibitor-treated specimens showed finer and more uniform grain structures with less surface etching. Grain boundary damage was reduced, suggesting that bioactive compounds in AHHE adsorbed onto the steel surface to form a protective layer, slowing the corrosive attack. This effect was most pronounced at 30% AHHE, where micrographs revealed a smoother surface with minimal localized damage. The preservation of grain boundary definition and the reduction in surface roughness across the 7 to 21 days range indicate that AHHE not only slowed corrosion but also helped maintain the steel's microstructural stability in alkaline environments.

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Table 1. Macrostructure of sample in an alkaline (NaCl) medium

AISI 1020	0% extract concentration	10% extract concentration	20% extract concentration	30% extract concentration
7 days				
14 days				
21 days				

Similar improvements in surface preservation have been reported for other plant-based inhibitors. Sadiq et al. (2015) observed reduced grain boundary attack and smoother steel surfaces when neem (Azadirachta indica) leaf extract was used in alkaline conditions. Likewise, Karim et al. (2016) showed that Citrus aurantium extract effectively maintained surface morphology and limited localized corrosion of mild steel in a similar environment. These parallels reinforce the conclusion that AHHE offers a sustainable and effective approach for protecting carbon steel in alkaline media. Table 2 presents the comparative optical micrographs for immersion periods of 7, 14, and 21 days at 0%, 10%, 20% and 30% AHHE, clearly illustrating the progressive improvement in surface preservation with increasing inhibitor concentration.

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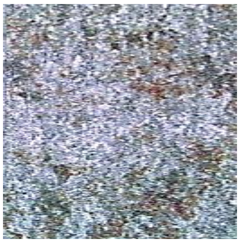
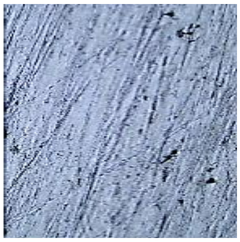
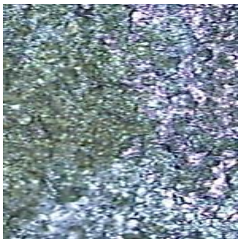
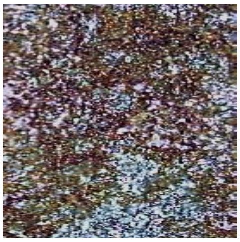
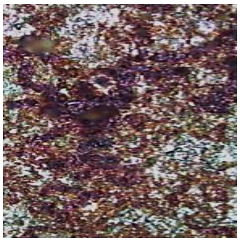
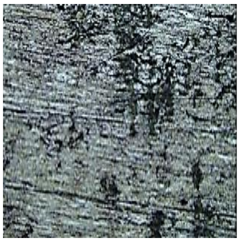
Table 2. Microstructure of the sample in an alkaline (NaCl) medium

AISI 1020	0% extract concentration	10% extract concentration	20% extract concentration	30% extract concentration
7 days				
14 days				
21 days				

CONCLUSION

This study confirms that both inhibitor concentration and immersion period significantly influence the corrosion performance of AISI 1020 mild steel. Increasing the inhibitor concentration from 0% to 30% progressively reduced the corrosion rate, with the most pronounced improvement observed at the addition of 30%. Although the reduction rate tapered at higher concentrations, inhibition efficiency continued to improve, reflecting stronger and more stable surface protection. Extended immersion in the absence of the inhibitor led to severe surface deterioration, whereas higher concentrations maintained surface integrity through the formation of a persistent protective film. FTIR analysis identified hydroxyl and carboxyl groups, supporting the role of strong adsorption in sustaining corrosion resistance over time. These results demonstrate that higher inhibitor concentrations provide both immediate and long-term protection, particularly in environments requiring extended exposure.

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CONFLICT OF INTEREST STATEMENT

The authors affirm that this study was carried out without any personal gain or involvement in commercial or financial conflicts. They also declare that there are no competing interests related to the funding sources.

AUTHORS' CONTRIBUTIONS

The authors confirm their contribution to the paper as follows: study conception and design: Masalina Md Ali, Siti Khadijah Alias, Muhammad Amir Mat Shah, Bulan Abdullah; data collection: Masalina Md Ali, Munzir Izhar Hisham, Hazriel Faizal Pahroraji; analysis and interpretation of results: Masalina Md Ali, Siti Khadijah Alias, Najwa Delaila Tumin; draft manuscript preparation: Masalina Md Ali, Munzir Izhar Hisham, Nik Masmiati Nik Pa. All authors reviewed the results and approved the final version of the manuscript.

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