THE EFFECTIVENESS OF WASTE MATERIAL FROM THE KITCHEN AS A CORROSION INHIBITOR FOR AISI 1020 CARBON STEEL IN AN ACIDIC ENVIRONMENT

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ABSTRACT: *Corrosion inhibitors are widely used to reduce the degradation of metals exposed to aggressive environments. However, many conventional inhibitors present several disadvantages, including high cost, toxicity, and potential environmental hazards. Due to increasing environmental awareness and stricter regulations, significant attention has been directed toward the development of environmentally friendly and biodegradable corrosion inhibitors. Eggshell (ES) waste, which is mainly contain of calcium carbonate ($CaCO_3$), has recently emerged as a promising green material for corrosion protection applications. In this study, the corrosion inhibition performance of ES on AISI 1020 carbon steel immersed in 1.0 M hydrochloric acid (HCl) was evaluated using the weight-loss technique over a three-day immersion period. The physicochemical characteristics of the ES were analyzed by using Fourier Transform Infrared Spectroscopy (FTIR) to recognize the functional groups. In addition, Scanning Electron Microscopy (SEM) was employed to observe the surface morphology of the steel samples after immersion in the acidic solution. The results showed that the addition of ES significantly reduced the corrosion rate of steel, achieving a maximum inhibition efficiency of 99.74%. This high efficiency indicates the formation of a protective barrier layer on the metal surface due to the adsorption of $CaCO_3$ compounds. Furthermore, the inhibition efficiency increased with increasing inhibitor concentration, demonstrating a concentration-dependent inhibition mechanism. These findings confirm that eggshell powder is an effective and environmentally sustainable corrosion inhibitor for acidic environments.*

KEYWORDS: *Corrosion Inhibitor; Carbon Steel; Waste; FTIR*

1.0 INTRODUCTION

Corrosion is a natural degradation process that mains to the deterioration of carbon steel surfaces through their interaction with the surrounding environment. This phenomenon becomes more severe in aggressive acidic or alkaline conditions, which are commonly encountered in oil and gas pipelines, boilers, offshore platforms, and structural components [1], [2]. Considering that carbon steel accounts for more than half of the metallic materials used in industrial applications, corrosion remains a critical engineering and economic concern. Corrosion results in significant global economic losses, costing around USD 2.5

trillion with equivalent to 3-4% of global GDP [3].

Corrosion generally occurs by two mechanisms, including chemical or electrochemical [4]. These processes occur when metals are exposed to environments such as seawater [5], [6], industrial waste, or acidic solutions [7], [8], prominent in oxidation reactions and progressive material degradation. The electrochemical process involves anodic and cathodic reactions that gradually weaken the material. Over time, this deterioration may result in mechanical failure, safety hazards, and costly maintenance or replacement.

Various approaches have been developed to reduce corrosion, including galvanization, painting, electroplating, protective coatings, and cathodic protection. Among these methods, corrosion inhibitors are widely used for their practicality and cost-effectiveness, particularly on internal surfaces exposed to corrosive media. Corrosion inhibitors are generally classified into inorganic and organic compounds. However, with growing environmental awareness and increasingly strict regulatory requirements, the development of environmentally friendly and natural corrosion inhibitors has attracted considerable attention in recent years. [9]-[11].

Natural organic compounds derived from plant extracts have been extensively investigated as green corrosion inhibitors. Numerous studies have reported the effectiveness of extracts from *Ruellia tuberosa L* [12], *Mussaenda frondose*[13], *Macaranga peltate* [14], *Terminalia catappa* [15], and *Caesalpinia spinosa* extracts [16] in acidic media. These natural inhibitors are rich in bioactive constituents, including tannins, alkaloids, flavonoids, and polyphenols, as well as heteroatoms such as nitrogen (N), oxygen (O), phosphorus (P), and sulfur (S) [17]-[19]. The existence of these heteroatoms and unsaturated functional groups enhances adsorption onto the metal surface, which reduces anodic dissolution.

The corrosion inhibition mechanism of these organic molecules is primarily due to their ability to donate lone-pair or π-electrons to vacant d-orbitals on the metal surface, forming a protective adsorbed film [19]. The adsorption process may occur either by physisorption or chemisorption, depending on environmental conditions. The effectiveness of heteroatoms in corrosion inhibition generally follows the order O < N < S < P, indicating stronger adsorption interactions for molecules containing sulfur and phosphorus atoms [20]. Many plant-based inhibitors have demonstrated inhibition efficiencies exceeding 90%, such as *Ceratonia siliqua* L. seeds (up to 95.30%) [21], *Centrosema pubescens* leaves extract (85.37%) [22], and *Tinospora cordifolia* extract (94.73%) in 1 M HCl medium [23]. These findings verify the strong potential of natural compounds as sustainable corrosion inhibitors for mild steel in acidic environments.

In addition to plant extracts, waste-derived materials have also gained attention as alternative green corrosion inhibitors. Eggshell (ES), an abundant form of kitchen waste, is particularly promising due to its high mineral content. ES consists of approximately 95% calcium carbonate ($CaCO_3$), along with small amounts of calcium phosphate and other organic components. Calcium carbonate is known to improve thermal stability, mechanical strength, and biocompatibility in various applications. In corrosion systems, $CaCO_3$ can contribute to corrosion protection by forming a protective barrier layer on the metal surface, modifying the local pH environment, and stabilizing passive oxide films. [2], [24].

In addition to its mineral composition, ES contains organic biomolecules, such as amino acids and proteins, that may enhance surface interactions with metal substrates [25], [26]. The presence of calcium ions and carbonate species may facilitate the formation of a compact protective layer that reduces direct contact between the metal surface and the aggressive acidic environment. Since calcium and $CaCO_3$ are the dominant constituents of ES, it is logically significant to investigate their potential as natural corrosion inhibitors, particularly

in acidic media where carbon steel is highly susceptible to corrosion. Therefore, this study aims to investigate the effect of ES at various concentrations on the corrosion behaviour and inhibition efficiency of AISI 1020 carbon steel in 1 M hydrochloric acid (HCl). By converting waste materials into functional corrosion inhibitors, this research supports sustainable materials engineering, aligns with the principles of green chemistry, and promotes environmentally responsible corrosion protection strategies.

2.0 METHODOLOGY

2.1 Selection of Chemicals and Materials

AISI 1020 specimens were selected as the substrate material for this study. The steel plates were mechanically cut into rectangular specimens to ensure consistency throughout the experimental procedures. Before corrosion testing, the chemical composition of the steel samples was determined using an arc-spark emission spectrometer to verify compliance with the carbon-steel standard specification. The detailed elemental composition obtained from the spectrometric analysis is given in Table 1.

Table 1: Element of carbon steel

Elements	Chemical Composition (%)
Ferrum	98.60
Manganese	0.560
Carbon	0.316
Phosphorus	0.022
Silicon	0.168
Sulphur	0.012

A natural corrosion inhibitor was prepared by collecting ES waste from bakeries and restaurants in Bandar Seri Alam, Masai, Johor, Malaysia. Then, ES were washed with distilled water to remove remaining organic matter and boiled to eliminate impurities and microbial contaminants. The cleaned ES were then oven-dried to completely remove moisture. Subsequently, the dried ES were ground in a high-speed grinder. The resulting powder was sieved using a vibrating sieve to obtain a uniform, fine particle size distribution suitable for extraction and corrosion testing. The extraction process was carried out using ethanol as the solvent in a reflux extractor. The extraction duration ranged from 3 to 6 hours to ensure efficient extraction of active constituents. After extraction, the obtained inhibitor solution was prepared at different concentrations (Blank (0g), 1 g, 3 g, 5 g, 7 g, 9 g, 11 g, 13 g, and 15 g) for the following corrosion evaluation.

2.2 Characterization of the Waste Kitchen

The characteristics of the ES from kitchen waste were analysed using Fourier Transform Infrared Spectroscopy (FTIR). FTIR analysis was conducted to determine the chemical composition, and functional groups present in the material, particularly to confirm the presence of $CaCO_3$, heteroatoms, and other mineral constituents. A small quantity of finely powdered sample was subjected to FTIR analysis using a PerkinElmer Spectrum instrument within a scanning range of 400–4000 cm^{-1}. This spectral range enables the identification of characteristic vibrational bands associated with carbonate groups (CO_3^{2-}), hydroxyl groups (–OH), and other functional moieties that may contribute to corrosion inhibition through

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adsorption mechanisms.

2.2 Weight Loss Test

The static weight-loss technique was employed to estimate the corrosion-inhibition performance of ES powder on AISI 1020 in an acidic medium. The corrosion rate was determined in accordance with the American Society for Testing and Materials (ASTM) G1-03 standard [27]. This method is widely recognized for assessing metal degradation in corrosive environments by quantifying mass loss over a defined exposure period.

Before immersion testing, the steel specimens were mechanically polished using progressively finer grades of silicon carbide (SiC) abrasive paper; from 240 up to 1200 grit, to achieve a smooth, uniform surface finish. The polished samples were then rinsed with distilled water, dried, and degreased with acetone to eliminate any residual organic contaminants that could interfere with the corrosion process. The pre-weighed rectangular steel specimens were immersed in 200 mL of 1 M HCl solution, with or without ES, at various concentrations. The immersion tests were conducted under static conditions for exposure periods of 3, 5, and 7 days at room temperature. Upon completion of the exposure period, the specimens were thoroughly rinsed to remove corrosion products, dried, and reweighed to determine the final mass.

The corrosion rate (CR) was calculated from the mass loss of the specimens before and after immersion. At the same time, the inhibition efficiency (IE%) was determined by comparing the weight loss in the with and without of the inhibitor, as expressed by Equations (1) and (2), respectively.

$$CR = (K \times W)/(A \times T \times D) \quad (1)$$

$$Inhibition\ Efficiency\ (\%) = \frac{CR_{inh,0} - CR_{inh}}{CR_{inh,0}} \times 100 \quad (2)$$

where K is a constant value, W is the mass, A is the specimen area, T is the exposure time, and D is the density. CR_{inh} is with inhibitor, and $CR_{inh,0}$ is without inhibitor.

2.3 Microstructure Observations

Scanning Electron Microscopy (SEM) was used to examine the surface morphology and microstructural features of the specimens after corrosion testing. SEM is a powerful analytical technique capable of providing high-resolution surface imaging and detailed topographical information. The SEM system used in this study was a JEOL JSM-6380LA (Japan), which allows magnification ranging from 10× to 30,000×. For this investigation, magnifications of 1000× were selected to clearly capture the surface characteristics and corrosion features of the steel specimens.

Specimen selection for SEM analysis was based on corrosion performance results from weight-loss tests. Representative samples were chosen to reflect the most significant differences in corrosion behaviour under various experimental conditions. The specimen immersed in the blank solution (1 M HCl without inhibitor) was used as the reference sample for comparison with the specimen exposed to the optimum inhibitor concentration. Based on

the corrosion rate results, specimens immersed in the blank solution and in the solution containing 15 g of ES were selected for detailed surface morphology and elemental composition analysis.

After completion of the immersion tests (3 to 7 days), the selected specimens were carefully rinsed with distilled water to remove loosely adhered corrosion products. The samples were then dried, vacuum sealed, and stored in a desiccator to prevent further oxidation or contamination before SEM examination. The SEM analyses provide comprehensive insight into the surface degradation behaviour and protective effect of ES on carbon steel in acidic media.

3.0 RESULTS AND DISCUSSION

3.1 Fourier Transform Infrared Spectroscopy Result

The chemical structure and functional groups of the ES were analysed using FTIR. FTIR spectra were obtained for ES prepared at different concentrations, and the corresponding results are presented in Figure 1. The FTIR spectra confirm that calcium carbonate ($CaCO_3$) is the dominant component of the ES, which is consistent with the known composition of natural eggshells. Characteristic absorption bands associated with carbonate ions (CO_3^{2-}) were clearly observed. From the result, the highest peak in the range of 1410–1420 cm^{-1} corresponds to the asymmetric stretching vibration of the carbonate group. The sharp band near 874.39 cm^{-1} is, and 711.92 cm^{-1} are attributed to the out-of-plane bending vibration of carbonate ions. A broad absorption band between 3230 and 3500 cm^{-1} is associated with O–H stretching vibrations, which may originate from physically adsorbed water molecules or surface hydroxyl groups. These prominent peaks are characteristic of calcite-type $CaCO_3$ and confirm its presence as the principal element in the ES, consistent with other researchers [28], [29].

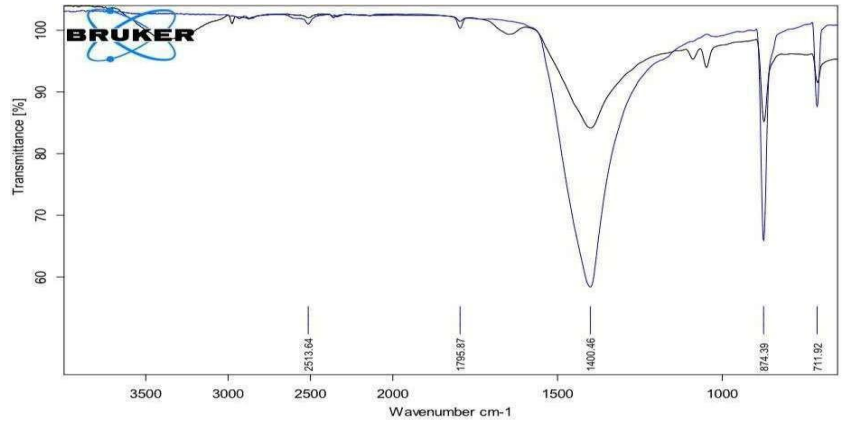

Figure 1: FTIR Result for Eggshell

3.2 Weight Loss Result

The weight loss technique was used to compare ES concentration at different immersion times. Table 2 shows the corrosion rate and inhibition efficiency (%) of carbon steel in 1.0 M HCl solution at 3, 5, and 7 days for the specific ES concentrations. Figure 2 shows the CR and IE of ES concentration. The results show that the Blank (0g) ES experienced the most corrosion damage, showing a corrosion rate of 3.6965 mm/y after 3 days of immersion. When 1g of ES

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was added to the solution, the corrosion rate significantly reduced to 0.5748 mm/y, representing a reduction of more than 84% compared to the specimen without inhibitor. This result indicates that the presence of ES effectively slowed down the corrosion process. Furthermore, the corrosion rate continued to decrease gradually as the ES concentration increased, reaching the lowest values at 15g, suggesting improved protection with higher inhibitor concentration.

Table 2: Corrosion rate and inhibitor efficiency at 3 to 7 days

Concentration (g)	Corrosion Rate (mm/y)	Inhibitor Efficiency (%)	Corrosion Rate (mm/y)	Inhibitor Efficiency (%)	Corrosion Rate (mm/y)	Inhibitor Efficiency (%)
	3 Days	3 Days	5 Days	5 Days	7 Days	7 Days
Blank	3.6965	0.0000	6.812	0.0000	9.2227	0.0000
1	0.5748	84.4511	1.2944	64.9838	1.9849	90.8036
3	0.3970	89.2606	1.206	67.3737	1.05	95.1353
5	0.3997	89.1860	0.5197	85.9398	0.9285	95.6981
7	0.3075	91.6804	0.4905	86.7314	0.8598	96.0162
9	0.2617	92.9201	0.3597	84.8593	0.6118	97.1656
11	0.1960	94.6975	0.2886	92.1932	0.443	97.9475
13	0.1353	96.3406	0.1139	96.9181	0.4222	98.0439
15	0.1347	96.3555	0.0939	97.4608	0.0559	99.7408

A similar trend in corrosion behaviour was also observed for specimens immersed for 5 days. The blank showed the most severe corrosion attack, with the highest corrosion rate of 6.812 mm/y. However, when ES was added, the corrosion rate decreased significantly. At a concentration of 1g, the corrosion rate dropped to 1.2944 mm/y, indicating a substantial improvement in corrosion protection. At 9g, the corrosion rate continued to decrease to 0.3597 mm/y, and the lowest corrosion rate of 0.0939 mm/y was recorded at a concentration of 15 g.

During the 7-day immersion period, a similar trend was observed, where corrosion became more severe when the inhibitor was not present. The blank specimen recorded a high corrosion rate of 9.2227 mm/y, indicating that prolonged exposure to the acidic solution accelerated the dissolution of the metal surface. When 1 g of ES, was added, the corrosion rate reduced to 1.9849 mm/y. At 9g, the corrosion rate was further reduced to 0.6118 mm/y, while the highest concentration of 15g provided the most effective protection, with the corrosion rate decreasing to 0.0559 mm/y. This result suggests that higher concentrations of ES are more effective in reducing corrosion of the steel surface.

The results show that increasing the concentration of ES improves the corrosion resistance of the steel. This indicates that the inhibition performance depends on the amount of inhibitor present in the solution. When the concentration of ES is higher, more inhibitor particles are available to cover the steel surface. This coverage forms a protective layer on the metal surface, acting as a barrier between the steel and the acidic solution. As a result, the direct interaction between the metal and the corrosive medium is reduced, leading to a lower rate of metal dissolution [2], [30].

In addition, longer immersion times led to higher corrosion rates for the samples without an inhibitor. This shows that continuous exposure to the acidic solution increases corrosion severity. The presence of active hydrogen (H^+) and chloride (Cl^-) ions in HCl solution accelerates corrosion over time. Without the presence of eggshell extract, the metal surface is directly exposed to the corrosive medium, allowing the corrosion reaction to occur more rapidly. As a result, the steel undergoes faster anodic dissolution and greater material degradation.

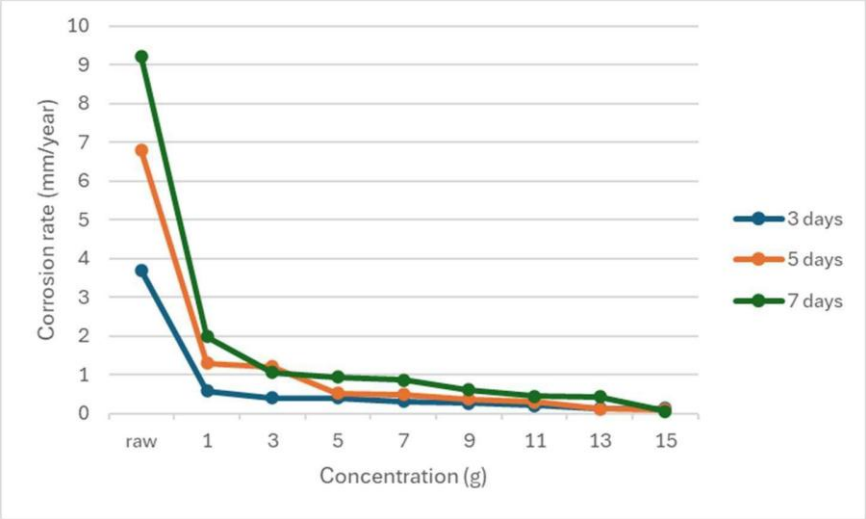

Figure 2: Corrosion rate against different concentrations

Figure 3 illustrates the inhibition efficiency of the samples at different ES concentrations. Unlike the corrosion rate, the inhibition efficiency increased as the ES concentration increased. At 3 days of immersion, the highest inhibition efficiency of 96.36% was obtained at the maximum ES concentration, corresponding to the lowest corrosion rate of 0.1347 mm/y. For the 5-day immersion period, the inhibition efficiency further improved, reaching 97.46% at the highest eggshell concentration, with a corresponding corrosion rate of 0.0939 mm/y. Similarly, after 7 days, the inhibition efficiency remained very high at 99.74% when 15 g of eggshell was used, indicating strong corrosion protection. These results suggest that both increasing ES concentration and longer immersion time contribute to better corrosion protection of mild steel. With longer exposure, more inhibitor species can interact with the metal surface, allowing stronger adsorption of the ES components in the 1.0 M HCl solution. The high $CaCO_3$ content in the eggshell also helps form a protective barrier layer on the steel surface, which limits the direct contact between the metal and the corrosive medium.
[2], [31].

In comparison, previous studies have shown that both inhibitor concentration and immersion time significantly influence corrosion inhibition performance. An increase in inhibitor concentration generally leads to higher inhibition efficiency because more inhibitor molecules are available to adsorb onto the steel surface. This adsorption improves surface coverage and promotes the formation of a more compact protective film. The immersion time also affects the inhibition behaviour. At an early stage of exposure, more inhibitor molecules gradually attach to the metal surface as time increases. This process allows a protective layer to develop on the steel surface, which acts as a barrier and reduces the direct interaction between the metal and the corrosive environment [32]-[34].

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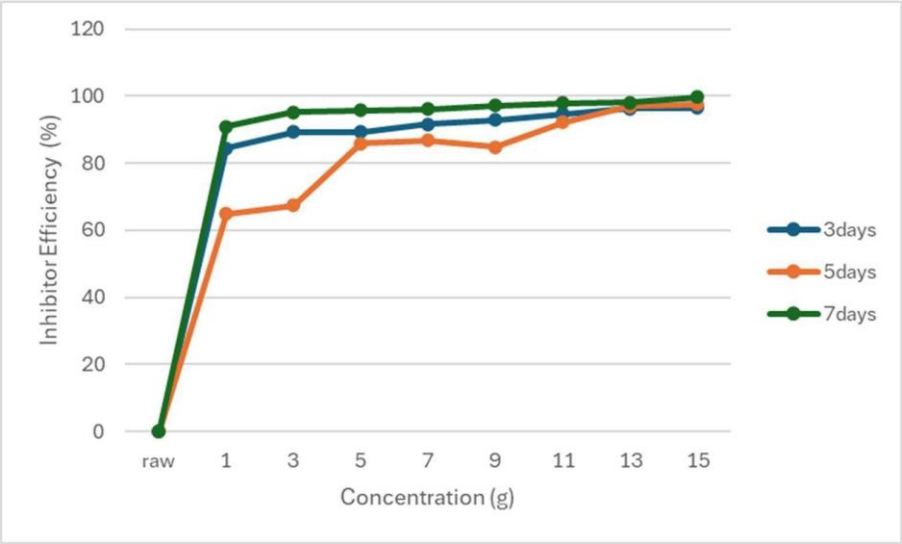

Figure 3: Inhibitor efficiency against different concentrations

3.3 Scanning Electron Microscopy- Energy Dispersive X-ray Spectroscopy (SEM-EDX)

Figure 4 presents the SEM image of carbon steel surfaces after immersion in 1 M HCl solution with and without the presence of ES. The surface morphology shown in Figure 4(a) represents the steel sample immersed in an acidic medium without any inhibitor. The surface appeared is severely damaged, with clear evidence of corrosion attack such as wide cracks, pits, and irregularly distributed corrosion products [33], [34]. These cracks indicate an intensive corrosion attack caused by the aggressive action of chloride ions (Cl^-) in the hydrochloric acid solution.

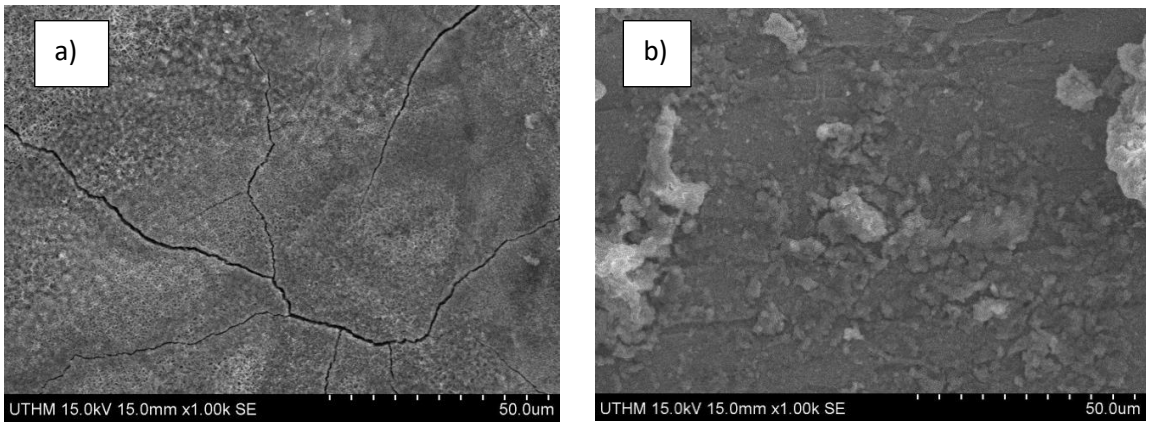

Figure 4: (a) Steel without inhibitor, (b) Steel with inhibitor

In contrast, the SEM image in Figure 4(b) shows a significant improvement in surface condition when ES is used as a corrosion inhibitor. The steel surface appears relatively smoother and more compact compared to the uninhibited sample. Some deposited particles can also be seen covering parts of the metal surface. These deposits are likely due to the adsorption of compounds from the ES, mainly calcium carbonate ($CaCO_3$), which helps form a protective layer on the steel surface. This protective film acts as a barrier that separates the

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metal from the acidic solution, thereby reducing the contact between the steel surface and aggressive ions in the corrosive environment. [31], [35], [36].

Previous studies by Farag Z et al. reported that steel surfaces exposed to uninhibited acidic solutions contain a high percentage of oxygen (O) and chlorine (Cl) elements. The increased oxygen content is usually associated with severe corrosion activity, which leads to higher surface roughness and the formation of corrosion pits on the iron matrix. These elements are typically related to corrosion products formed during the corrosion process in acidic media. Therefore, the SEM observations in this study provide clear morphological evidence that the eggshell extract functions as an effective green corrosion inhibitor for carbon steel in acidic environments by improving the surface condition and reducing corrosion damage [37].

4.0 CONCLUSION

In conclusion, this study investigated the effectiveness of ES as a natural corrosion inhibitor for carbon steel in an acidic medium. The overall findings are summarized as follows:

i) The study examined the potential of ES as a natural corrosion inhibitor for AISI 1020 carbon steel in 1.0 M HCl solution.
ii) FTIR characterization confirmed that ES is mainly composed of calcium carbonate ($CaCO_3$), which contributes to the corrosion inhibition behaviour.
iii) Corrosion tests conducted over 3, 5, and 7 days showed that the corrosion rate decreased as the eggshell concentration increased.
iv) The highest inhibition performance was obtained at 15g of ES, indicating that the effectiveness of the inhibitor is strongly influenced by its concentration.
v) Higher ES concentrations improve surface coverage and form a protective layer on the steel surface, while the presence of ES helps maintain corrosion protection even during longer immersion times.
vi) SEM observations revealed severe surface damage on uninhibited samples, while samples treated with higher ES concentrations showed smoother surfaces and reduced corrosion features.
vii) The findings indicate that ES has strong potential as a green, low-cost corrosion inhibitor for carbon steel while also promoting sustainable waste utilization in corrosion protection applications.

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