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ORIGINAL ARTICLE

# Corrosion Control of AISI 1007 Steel Using Hybrid Inhibitors of Plant Extracts

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**Abstract**
Owing to the adverse effects of corrosion, scientist have devised several means of its control. Amongst these means is the use of inhibitors which could be synthetic or from natural sources. Synthetic inhibitors are often toxic and expensive, hence inhibitors from natural source are preferred. Action of *Moringa oleifera* and *Jatropha curcas* leaves extracts have been independently explored for corrosion inhibition on metals. In this study, equal mixture of *Moringa oleifera* and *Jatropha curcas* leaves extract was examined for inhibiting corrosion on AISI 1007 steel in acidic medium via gravimetric, gasometric and thermometric analysis methods. The appropriate experimental techniques as recorded in previous studies and ASTM standards were adopted. It was observed that with each method used that the efficiency of inhibition increased with the rise in the inhibitor's concentration while the volume of hydrogen gas evolved increased with increasing inhibition concentration. The maximum inhibitive efficiency obtained on equal proportion of the mixture was 95.56%. The utilization of the hybrid extract from the two leaves gave superior inhibition efficiency than the independently used as extract as reported from previous studies. Hence, equal mixture of *Moringa oleifera* and *Jatropha curcas* leaves extract is recommended for utilization as potential inhibitor in industries.

**Keywords** Corrosion inhibitor · *Jatropha curcas* · *Moringa oleifera* · Plant extracts · Corrosion science

## 1 Introduction

Materials corrosion has continued to receive great attention for several decades from the scientific world because its occurrence is attached to numerous industrial and domestic losses [1, 2]. Corrosion is a destructive phenomenon, either chemical or electrochemical, which attacks metals or alloys because of their interactions with the environment and in extreme cases, leads to structural failure [2]. The occurrence of corrosion is not limited to metals only but affects every engineering material, but the common term used is "degradation". The useful properties of materials are degraded by corrosion activities. The impacts of corrosion on structural integrity of metals have been of serious concern over the years because it is an ever-occurring materials disease. The total prevention of corrosion occurrence is practically impossible because of its spontaneous thermodynamic phenomenon; however, its cost could be reduced [3].

Several methods of preventing corrosion have been discussed [4–7]. The acceptability of the utilization of inhibitors is in controlling and preventing corrosion is prevalent among the other corrosion ameliorating methods [6, 8, 9]. The reduction or prevention of the corrosion tendency of a material in a corrosive media is achievable through the introduction of corrosion inhibitors [7, 8]. Inhibitors may be synthesized or obtained from natural sources such as seeds or other plant parts. Synthetic inhibitors are highly applied in industries over the years due to their high anti-corrosion abilities. They can be obtained cheaply, but many of them show severe after-use effects such as the evolution of toxic substances into the environment [4, 8, 10].

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Despite the wide application of synthetic inhibitors in production and materials processing operations, the concern had been about the level of toxicity in most of these inhibitors. Hence, scientists shifted their attention to the use of environmental-friendly, biodegradable, inexpensive, and readily available naturally occurring substances [11]. Although, most synthetic compounds displayed decent anticorrosive activities; they are mostly accompanied with the release of high toxicity gases, which are injurious to human's health and environment. Hence, due to environmental regulations, their utilization is limited owing to the threat they pose on the environment [12]. Corrosion inhibitors of organic origin are found suitable in most corrosive media [13]. Organic compounds in plant extracts which are used as inhibitors are those that have multiple bonds in their molecules containing nitrogen, sulfur, and oxygen atoms through which they get adsorbed on the metal surface. Generally, good inhibition is achieved when compounds with π-bonds are used through the heteroatoms' electrons supply [12]. These heteroatoms are the active hubs for the adsorption process on the metal surface because of their higher basicity and electron density [13, 14]. Therefore, "green inhibitor" or "eco-friendly inhibitor" are substances which are biocompatible with the ecosystem. Plant extracts used as inhibitors can be presumably stated to be biocompatible with the ecosystem owing to their biological origin [14].

The existing data for the utilization of organic compounds in reducing corrosion occurrence on metals had revealed the adsorption of organic inhibitors on the metal surface through the displacement of water molecules and the formation of a solid barrier [14]. The transference of electron from the inhibitor to the metal is facilitated by the presence of lone pair (non-bonded) and p-electrons in molecules of the inhibitor. This could lead to the formation of a coordinate covalent bond between the inhibitor and the metal surface via electrons transfer. The chemisorption bond's strength is dependent on donor atom functional group's electron density and polarizable ability of the group [15]. The chemical structure as well as the physicochemical properties of organic inhibitors play a vital role in the determination of its performance [13]. The inhibition occurrence could be linked to the ionic or molecular adsorption on the anodic and cathodic sites, leading to an increased cathodic or anodic voltage; hence, the development of a protective barrier film [13].

Several authors have utilized different extracts from different parts of a plant, such as leaves, stems, and barks: as corrosion inhibitors in corrosive media [4, 6, 15–24]. Kumar et al. [25] studied the effect of using *Morus nigra* (Mulberry) leaves extract as green corrosion inhibitor for mild steel in 0.5 M HCl. The study revealed high corrosion inhibition of 91.62% when 1000 ppm inhibitor was used, with mixed inhibition phenomenon. The utilization of the *Phyllanthus amarus* ethanolic extract of corrosion inhibitor in 2 M HCl solution for mild steel was studied by Abeng et al. [26] It was reported that the inhibition efficiency rises while corrosion rate was lowered with the inhibitor's application. The mitigating capability of the extract from *Sonneratia caseolaris* leaf was studied on mild steel when subjected to HCl environment. The highest IE was 98% at 2500 ppm of the inhibitor with decrease in performance as the concentration of HCl decrease with same quantity of inhibitor. Odusote et al. [18] examined the ameliorative influence of utilizing the extract from *Moringa oleifera* leaf on the steel bar corrosion in 2 M solution HCl. The gravimetric, gasometric and potentiodynamic polarization techniques which were used to study the corrosion inhibiting potency of the extracts revealed a linear proportionality between the extract's concentration and the inhibition efficiency increases and about 92.31% efficiency was obtained after an exposure of about 120 h during gravimetric analysis.

Based on the literature surveys, the combination of two or more naturally sourced inhibitors is likely to have high inhibiting efficiency [15, 17]. This present study utilizes two plant extracts from *Jatropha curcas* and *Moringa oleifera*. The extracts have been reported with different methods to have high inhibitive efficiency individually [6, 27]. However, for the high efficiency of these extracts, the phytochemical constituents of two plants extract were examined and combined. The phytochemical constituents of mixed *Moringa oleifera* and *Jatropha curcas* were investigated, while the effect of the combined inhibition extracts on American Iron and Steel Institute 1007 steel (AISI 1007) in HCl acid solution was studied. The mechanisms of their corrosion inhibition were analyzed with respect to varying concentrations of the hybrid inhibitor.

## 2 Materials and Methods

### 2.1 Materials

A 1.5 mm thick metal sheet (AISI 1007) specimen was obtained from a local market in Ilorin, Nigeria. Optical emission spectroscopy was used to carry out composition analysis of the sample. *Moringa oleifera* and *Jatropha curcas* leaves were obtained from a plantation inside a University of Ilorin campus. Two solutions of 0.2 and 0.4 M from HCl were prepared by using distilled water in a laboratory.

### 2.2 Sample Preparation

The sheet of metal was cut into a dimension of 2.2 × 1.7 cm coupons and was marked by drilling hole of 1.5 mm in

the samples to aid easy removal from the solution. Emery papers of grade 320 and 800 were used to grind the specimens. The specimens were then degreased in ethanol and acetone respectively, dried and stored in desiccator to avoid contact with moisture.

## 2.3 Plant Extracts Preparation

Fresh leaves of *Moringa oleifera* and *Jatropha curcas* plants were each taken separately, washed, shade dried for six days. After, pulverization of the dried leaves was done and powder was sieved to maintain uniformity. The pulverized leaves were each soaked with ethanol in separate containers and left for 24 h before they were filtered. The filtrates were concentrated by placing each container in a water bath and heating until the whole ethanol has evaporated, leaving behind a paste.

## 2.4 Phytochemical Screening

The *Jatropha curcas* and *Moringa oleifera* leaves were separately placed in two different beakers where ethanol was used to dissolve the leaves in each beaker, allowed to soak, filtered and decanted. Quantitative analysis of each extract was carried out with different reagents following standards. The results were measured and recorded in mg.

### 2.4.1 Phenols

A portion of the extracts were each treated with four drops of $FeCl_3$ solution, the formation of bluish black color was observed which indicate the presence of phenols. 100 mg of the extract was obtained by weighing and it was dissolved in 100 ml of distilled water. 1ml of the solution was put into a test tube and 0.5 ml of 2 M foliu-ciocalteu reagent was added, followed by 1.5 ml 20% $Na_2CO_3$ solution, the volume of the solution in the test tube was raised to 8 ml by adding distilled water. The solution was vigorously shacked and allowed to settle for 2 h. The process was carried out for the two samples and the amount of phenols in each sample was estimated by weighing the residue after being allowed to dry.

### 2.4.2 Alkaloids

Another portion of the extracts were each dissolved in distilled hydrochloric acid, filtered, and then treated with potassium mercuric iodide solution and the formation of a whitish yellow colored precipitate was observed which indicate the presence of alkaloids. 100 mg of the extract was obtained by weighing, it was put into a beaker and 200 ml of 10% acetic acid was added. The solution was allowed to stay for 4 h and then filtered. Drop of concentrated $NH_4OH$ were added to each of extracts until precipitates were completely formed. The solutions were allowed to settle and then, decanted. The alkaloid residues in each sample were allowed to dry in ambient air and weighed to obtain the amount of alkaloid present.

### 2.4.3 Saponins

Another portion of the extracts were each diluted with distilled water up to 20 ml and shacked in a graduated test tube for 5 min. Layers of foam was formed which indicate the presence of saponins. 100 mg of the extracts were each weighed and put into separate flask, 100 $cm^3$ of 20% aqueous ethanol was added to each sample and the solution was heated to obtain a concentrate which was put into 250 ml beaker and 20 ml of diethyl ether was added. The solutions were vigorously shaken and aqueous layer were obtained. The solution was heated to evaporation. The dried sample was measured to determine the saponin content.

### 2.4.4 Tannins

A portion of the extracts were boiled in 20 ml of distilled water using a test tube and later filtered. Ferric oxide (0.1%) in few drops were added and a brownish green coloration was observed in each sample which indicates the presence of tannins. 100 mg of each extract were obtained by weighing and put into a beaker. 50 ml of distilled water was added, and the solution was shacked vigorously. The mixture was filtered and 2 ml of 0.1 M ferric chloride, 0.1 M HCl and 0.008 M potassium ferro-cynide were added in each sample. The resulting solutions were allowed to settle, and the residue was obtained by decantation, dried and weighed to estimate the amount present.

### 2.4.5 Flavonoids

Another portion of the extracts were each treated with few drops of ferric chloride solution and an intense green color was developed which indicate the presence of flavonoid. 100 mg of the extracts were each dissolved in 100 ml of ethanol and 100 ml of 20% aluminum trichloride. Few drops of acetic acid were added, and the solution was diluted with methanol up to 500 ml, then filtered and the residue was dried and weighed to obtain the number of flavonoids.

### 2.4.6 Terpenoids

A portion of the extracts were in separate test tube each mixed with 2 ml of chloroform and 3ml of sulphuric acid. Layers of reddish-brown coloration appear in the test tube

of *Moringa oleifera (MO)* extract indicating the presence of terpenoid. No observable layers of any color in the test tube of *Jatropha curcas* (JC) extract indicating the absence of terpenoid. Similar procedure was done for the detection of the presence of Oxalate and Anthraquinone, in each case was present in *Moringa oleifera* extract but absent in *Jatropha curcas* extracts.

## 2.5 Gravimetric Analysis

The volume of the solution to be used was predetermined by measuring up to one-third of the total volume of the container to be used for immersion. The predetermined volume (750 ml) of 0.2 M HCl solution was measured and poured into each beaker. Five of the containers were made to contain no inhibitor and were marked as blank while five containers each were made to contain an equal proportion of 0.2, 0.4, 0.6, and 0.8 g of *Moringa oleifera* and *Jatropha curcas* extracts making a total of 25 setups. The prepared metal samples were taken from the desiccators, weighed, and suspended by thread in each of the containers. The samples in each of the blank, 0.2, 0.4, 0.6, 0.8 g solution of MO and JC were each brought out after 24 h, cleaned in ethanol and acetone and reweighed to obtain the final mass of the sample. The process was repeated for five days and the resulting loss in weight of each sample was recorded by comparing the final weight of the specimen in each day with the original weight of the specimen. Using the weight loss values, corrosion rate and percentage inhibition efficiency were calculated using the Eq. (1).

$$CR(gcm^{-2}h^{-1}) = \frac{\Delta w}{At} \tag{1}$$

where CR, ΔW, A and t represents the corrosion rate, weight loss (g), total area of the substrate ($cm^2$), and immersion period (h), respectively.

The inhibition efficiency (IE %) was then evaluated using Eq. (2) [18]:

$$I.E(\%) = \left(1 - \frac{CR\,inh}{CR\,blank}\right) \times 100 \tag{2}$$

where $CR_{inh}$ and $CR_{blank}$ are the corrosion rates in the presence and absence of the extracts, respectively.

## 2.6 Gasometrical Analysis

The gasometrical assembly that was utilized for the determination of $H_2$ evolution was similar to that stated by Odusote et al. [18]. A 250 ml of 0.4 M HCl solution was introduced into 1000 ml Buckner flask and the initial volume of water in the burette were recorded. The weighed sample was released into the HCl media, and the flask was immediately covered to prevent the discharge of gases. The $H_2$ gas volume evolved due to the corrosion reaction was noted via the volumetric change in the water level in the burette and the absorption time was noted with the volumetric change being recorded at interval of 120 to 1440 s. Similar technique was followed for a new solution with different inhibition concentration of equal proportion of mixture of 0.2, 0.4, 0.6 and 0.8 g. Hence, Eqs. (3) and (4) were employed for the evaluation of the I.E and the surface coverage, respectively [18].

$$Inhibition\ Efficiency\,(I.E)\,\% = \frac{VHO - VH1}{VHO} \times 100 \tag{3}$$

$$Surface\,coverage,\,\theta = \frac{VHO - VH1}{VHO} \tag{4}$$

where $V_{H0}$ and $V_{H1}$ are the volume of $H_2$ gas evolved without inhibitor and with inhibitor, respectively.

## 2.7 Thermometric Analysis

Using the technique highlighted by Odusote et al. [18], the AISI 1007 steel coupon of dimension 2.2×1.7×0.15 cm was immersed in 30 ml of test solutions of 0.4 M HCl acid solution with and without the inhibitor with varying concentrations of 0.2, 0.4, 0.6, and 0.8 g. The initial temperature was maintained at room temperature. The variation of temperature vs. time through a standard digital thermometer was used for the determination of the corrosion reaction process. Based on the temperature rise (per min), the reaction number (RN), I.E (%) and θ were calculated using Eq. (5) to (7), respectively [27].

$$Reaction\ Number\,(RN)\,(^oC\,min^{-1}) = \frac{(Tm - Ti)}{t} \tag{5}$$

$$Inhibition\ Efficiency\ (\%) = \left[\frac{(RNaq - RNwi)}{RNaq}\right] \times 100 \tag{6}$$

$$Surface\,Coverage\ (\theta) = \frac{(RNaq - RNwi)}{RNaq} \tag{7}$$

where Tm and Ti are the maximum and initial temperatures (°C) respectively. T, RNwi and RNaq are the period to reach the maximum temperature (min), reaction number with or without the inhibitor.

**Table 1** Elemental constituent of the AISI 1007 steel

| Element | wt% | Element | wt% |
|---|---|---|---|
| Fe | 99.500 | Ni | <0.0015 |
| C | 0.0477 | Al | 0.0103 |
| Si | 0.0392 | Co | 0.0049 |
| Mn | 0.2210 | Cu | 0.0182 |
| P | 0.0145 | Mg | <0.0010 |
| S | 0.0098 | Sb | 0.0023 |
| Cr | 0.0395 | Ta | 0.0438 |
| Mo | <0.0010 | Zn | 0.0038 |

**Table 2** Phytochemical analysis of *Moringa oleifera* and *Jatropha curcas*

| S/N | Constituent | *MO* leaves (mg) | *JC* leaves (mg) |
|---|---|---|---|
| 1 | Alkaloids | 2.30 | 3.86 |
| 2 | Tannins | 9.32 | 6.73 |
| 3 | Flavonoids | 3.86 | 2.69 |
| 4 | Phenolics | 3.82 | 0.38 |
| 5 | Steroids | 3.16 | 0.26 |
| 6 | Saponins | 1.78 | 5.12 |
| 7 | Glycosides | 0.22 | 0.22 |
| 8 | Terpenoids | 4.44 | - |
| 9 | Oxalate | 4.60 | - |
| 10 | Anthraquinone | 10.90 | - |
| 11 | Phytate | - | 0.38 |

## 3 Results and Discussion

### 3.1 Elemental Analysis of the Substrate

The elemental constituents of the metal used as the substrate in this study is displayed in Table 1. The result shows that the carbon content in the sample is 0.0477 wt%, which corresponds to the American Iron and Steel Institute 1007 steel. This suggests that the sample can be classified as AISI 1007 steel as well as a low carbon steel.

### 3.2 The Phytochemical Analysis

The quantitative analysis of the *Moringa oleifera* (MO) and *Jatropha curcas* (JC)leaves extracts is presented in Table 2. The result revealed that among the phytochemical constituents of *Moringa oleifera* leaf are Terpenoids, Oxalate and Anthtraquinone which are not present in the *Jatropha curcas* leaf. Meanwhile, phytate is present in the JC leaf but absent in MO leaf. This means that the combination of the extracts could allow for the presence of all the constituents. For every inhibitor, tannins, alkaloids, flavonoids, saponins, and others were present in their extracts [7, 28–30].

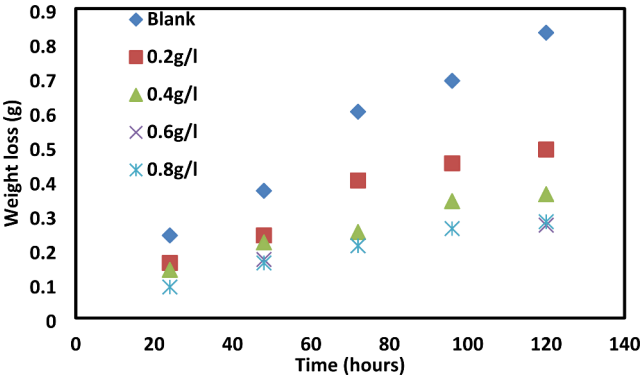


**Fig. 1** Weight loss variation with time for corrosion of AISI 1007 steel in 0.2 M HCl solution

### 3.3 Gravimetric Analysis

The difference in weight loss for corrosion of AISI 1007 steel with time in 0.2 M HCl media containing various concentrations of equal proportion mixture of *Moringa oleifera* and *Jatropha curcas* extracts is displayed in Fig. 1. As observed, the AISI 1007 steel weight loss decrease as the concentration of inhibitor increases while it rises as the exposure time increase. This reflects that the CR of AISI 1007 steel declines as the inhibitor concentration increases but increases with the time of exposure. This is probably due to the inhibitor adsorption rate on the metal surface which is in line with the individual action of *Moringa oleifera* and *Jatropha curcas* leaf extract as observed by Odusote et al. [18] and Odusote and Ajayi [27], respectively. Furthermore, there is an indication that the loss in weight increases as the immersion period increases for the uninhibited environment compared to the inhibited environment. Weight loss declines with increasing inhibitor concentration. Thus, the concentration of the hybrid inhibitors at 0.6 g/l and 0.8 g/l resulted in weight loss that are close in values. This reflects that the rate of corrosion of AISI 1007 steel is mitigated to a stable extent as the concentration increases. The phenomenon of inhibition could be linked to the adhesion of the active phytochemicals of the extracts of the leaves on the cathodic sites on the AISI 1007 steel. Therefore, the more the corrosion inhibitor concentration in the acidic environment, the better and higher will be the corrosion inhibitive action. More so, the phytochemicals present in the extracts are culpable to displaying better inhibition efficiency and mechanisms The active phytochemicals including phenol, tannins, saponins, and alkaloids in plant extracts are notable for variable inhibition mechanisms and efficiency [7, 31]. The molecular constituents of these extracts affect their inhibition tendency; thereby, affecting their reactivity and absorbability. This phenomenon could be attributed to the variation of the I.E and mechanisms described for various inhibiting agents. The reported declination in weight loss in

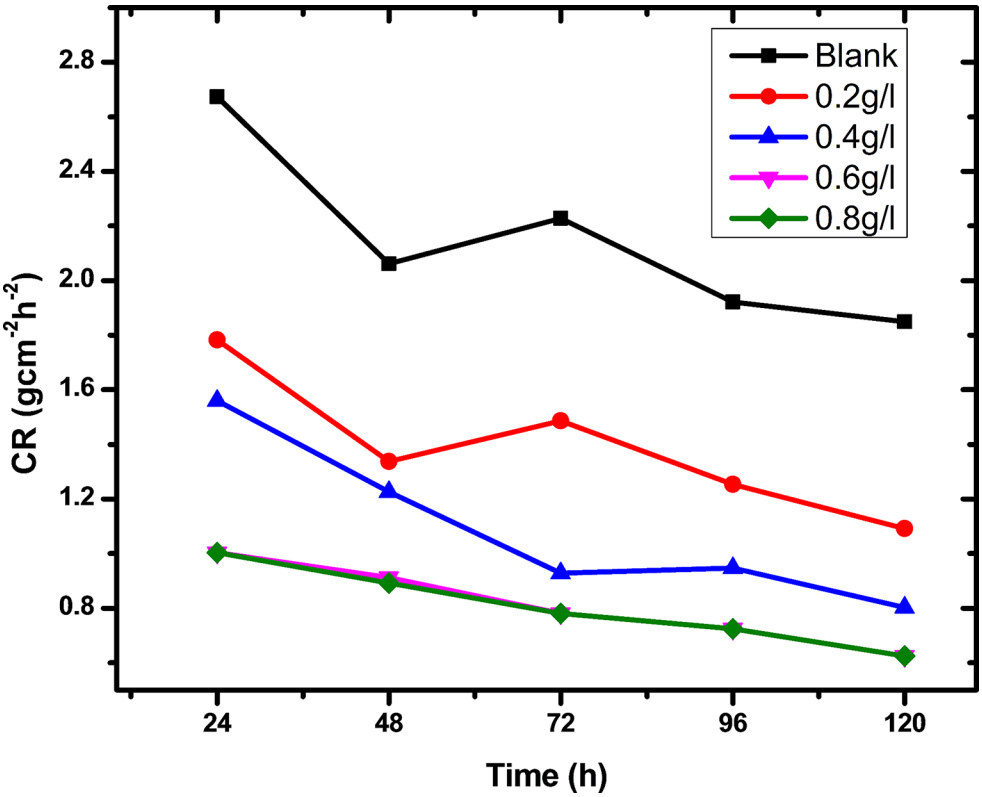


**Fig. 2** Variation of corrosion rate against time of immersion of the extract in 0.2 M HCl solution

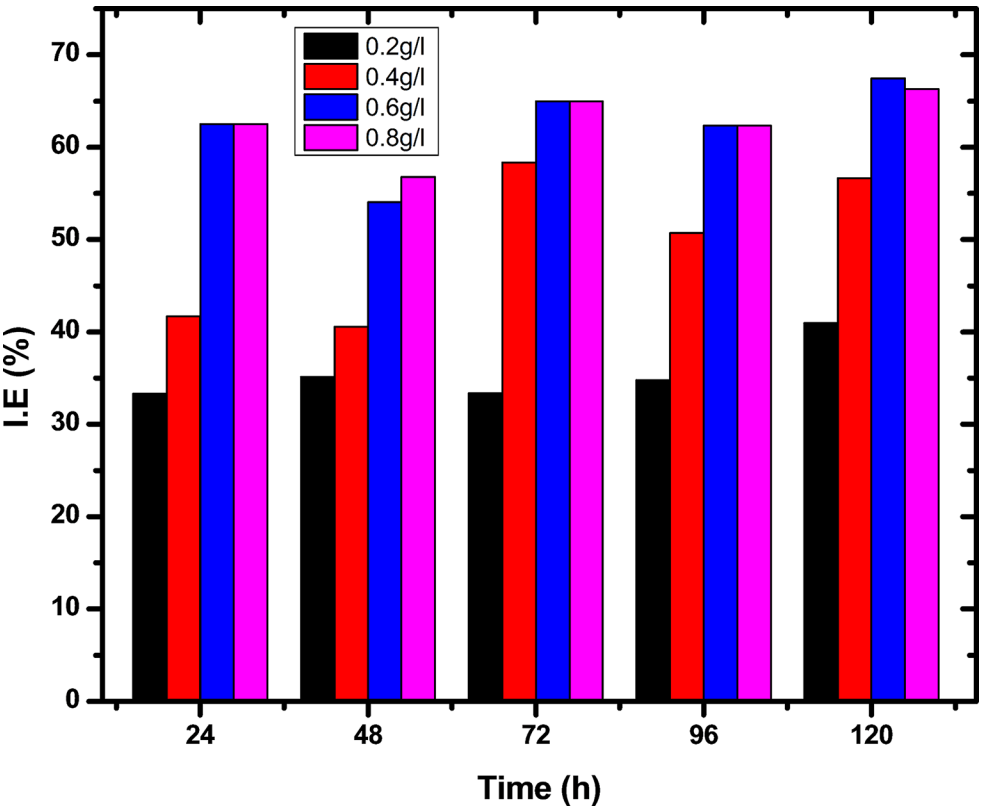


**Fig. 3** Percentage inhibition efficiency of equal mixture of *Moringa oleifera* and *Jatropha curcas* leaf extract in 0.2 M HCl solution at various immersion period

this study agrees with the pattern reported in literature [25, 26, 32]. Hence, the life span of the substrate is prolonged since the dissolution rate is lowered as the inhibition concentration is increased.

Figure 2 displays the variation of CR of AISI 1007 steel in varying concentration of equal proportion mixture of *Moringa oleifera* and *Jatropha curcas* leaf extract at different time of immersion. The CR lowers as the period of exposure increases. This shows that at a longer period, the specimen becomes passive to corrosion probably due to the development of inactive film on the substrate surface. This may have resulted from the action of *MO* leaf extract on the deterioration of the steel in HCl solution which is like the effect obtained by Odusote and Ajayi [27] on the inhibitive action of *JC* leaf extract for corrosion inhibition of mild steel in HCl media. The formation of inactive oxide on the surface of the AISI 1007 steel because of the ameliorative action of the hybrid green inhibitor, the corrosion rate is lowered. As the period of exposure increases, the CR becomes lower especially after the formation of active film. More so, more concentrations of the inhibitor affected the corrosion by gradual reduction. It can be inferred that the leaves' extracts of *MO* and *JC* are very effective owing to the high quantities of phytochemicals present in them and serve as good corrosion inhibitor in the corrosive environment.

Figure 3 presents the I.E of equal proportion mixture of *Moringa oleifera* and *Jatropha curcas* leaf extracts in 0.2 M HCl solution at varying immersion periods. The result indicates that I.E increases as concentration of the extracts increase. This reveals the development of an inactive film on the AISI 1007 steel surface which helps to prevent further direct corrosion attack on the steel specimen. Although, the coverage of the steel specimen surface by the inhibitor may also result in the increase in the percentage inhibition efficiency as the concentration of the extracts increase. Figure 3 also revealed that the IE of the inhibitor when the concentration is 0.6 g/l and 0.8 g/l are almost the same at different exposure time. The extract's IE could be linked to the existence of complex chemical compounds of active constituents [6, 7]. At the highest IE, there is an indication of the establishment of an indestructible barrier on the surface of the AISI 1007 steel causing the prevention of the

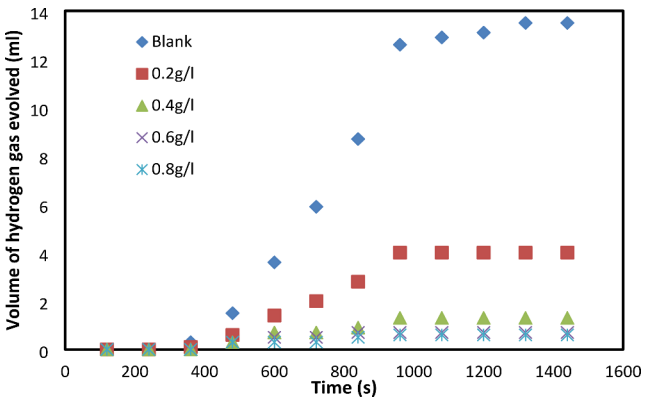


**Fig. 4** Evolution rate of hydrogen gas in 0.4 M HCl at various extract's concentration

further disintegration of the metal by the active constituents in the environment. More so, the inhibitor's IE is directly related to the concentration of inhibitor. Hence, the extracts of both leaves are adsorption corrosion inhibitors in HCl environment. Therefore, owing to the inhibitor's adhesion on the surface of the substrate, the favourable adsorption mechanism is the physical adsorption mechanism [7, 33].

### 3.4 Gasometric Analysis

The volume of $H_2$ gas evolution with time by the corrosion of AISI 1007 steel in 0.4 M HCl media with or without the inclusion of inhibitor is as displayed in Fig. 4. The result shows that the volumetric $H_2$ gas evolution increases as the exposure period increases but decreases with the rise in the concentration of the extract. This indicates that corrosion of AISI 1007 steel in 0.4 M HCl solution was inhibited by the leaves' extracts. There is variation in I.E (%) of the extracts with period of exposure in 0.4 M HCl acid medium. The result indicates that the I.E (%) increases with concentration of the extract and the period of exposure after initial total inhibition. More so, the volumetric hydrogen gas evolution at various concentrations of the extract in the 0.4 M HCl solution was presented in Fig. 4. It can be observed that prior to attaining a constant level of the volumetric hydrogen gas evolved, a direct relationship of increment was established between the $H_2$ gas volume evolved and time. Unlike the solutions without inhibitors, the solutions with inhibitors attained this constant level at a faster rate. By implication, the more the concentration of the inhibitor in a solution, the quicker will be activation of the passivity level. The observation that the proportionate increase in the volume of $H_2$ gas with period of exposure and reduction with increased inhibitor concentration was in line with the study of Odusote et al. [7] and Adekunle et al. [6]. This could be linked to the inhibition effects of the hybrid extracts depending on its degree of concentration. Therefore, corrosion rate (CR) of the AISI 1007 steel is slowed down by the phytochemical contents of the extract in the acidic media [34]. A high value of CR of the inhibited samples compared to the blank sample could be due to the gradual reduction of the adherent inactive oxide fil on the substrate. At 0.6 and 0.8 g/L concentration of the extracts, the rate of evolution of $H_2$ gas was observed to have reduced owing to the development of adsorption layer on the substrate's surface. Hence, corrosion inhibitor concentration increment in an acidic environment reduces the amount of hydrogen gas evolution.

Figure 5 revealed that total corrosion inhibition of AISI 1007 steel in 0.4 M HCl solution at 360 s was 100% which then decreases again before rising again as the period of exposure increases. This implies that the extracts are being absorbed on the substrate surface prior to the occurrence of

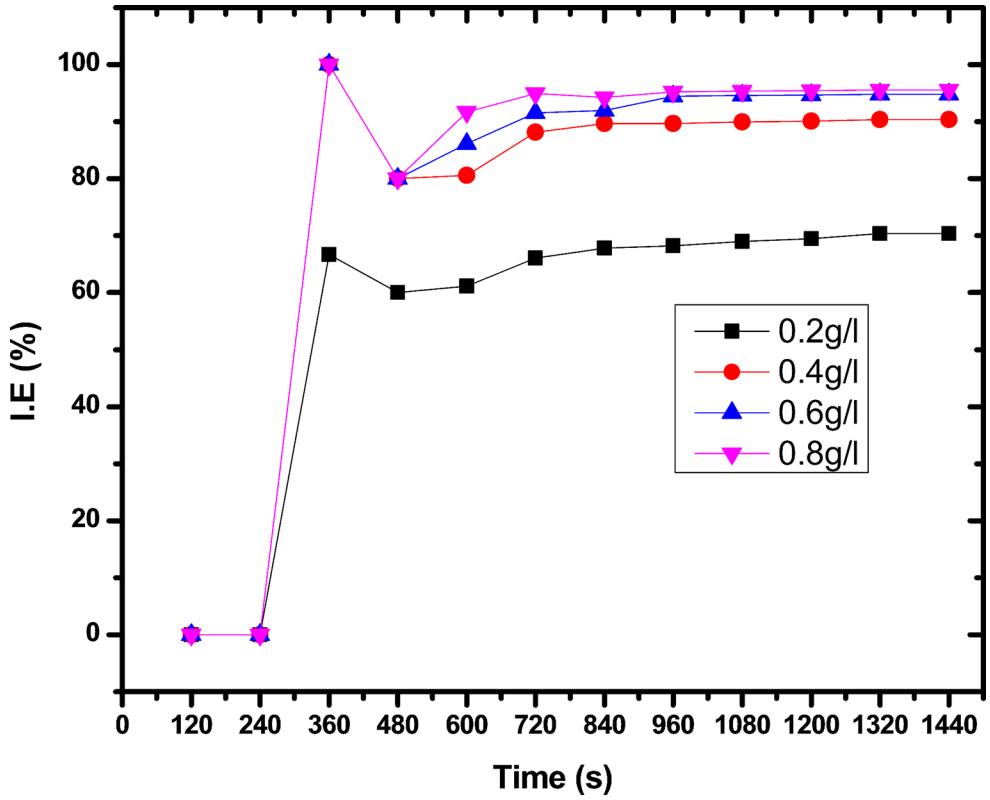


**Fig. 5** Inhibition efficiency vs. exposure time

**Table 3** Calculated values of the reaction number, I.E (%) and Θ at various concentration of the extracts

| MO + JC extract conc. (g/l) | RN (°C/min) | I.E (%) | Θ |
|---|---|---|---|
| Blank | 0.0722 | - | - |
| 0.20 | 0.0563 | 22.02 | 0.2202 |
| 0.40 | 0.0357 | 50.55 | 0.5055 |
| 0.60 | 0.0250 | 65.37 | 0.6537 |
| 0.80 | 0.0125 | 82.69 | 0.8269 |

RN - Reaction number, I.E – Inhibition efficiency, Θ – Surface coverage

corrosion hindrance. After the latent period of reaction initiation, the absorption time of the acid increased. Between the acid and oxide film on the substrate's surface, a slow reaction occurs at the latent period. CR and IE are always inversely related, that is, CR decrease means IE increase which could be attributed to the prevention of the acidic solution from reaching the surface of the substrate due to the barrier formed by passive oxide film. However, CR increase with reduced IE when the acid penetrates the surface of the substrate. The activeness of the inhibition from the extract on the substrate's surface is related to the action of the phytochemicals found in the extracts utilized. These observations agree with previous studies [6, 7, 35, 36].

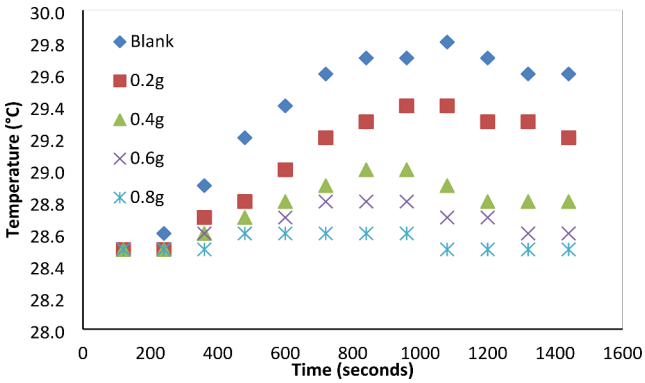


**Fig. 6** Temperature-time curves for corrosion of AISI 1007 steel in 0.4 M HCl solution

## 3.5 Thermometric Analysis

Table 3 shows the evaluated RN, I.E (%) and Θ at various concentrations of equal mixture of *Moringa oleifera* and *Jatropha curcas* leaf extract. The result shows that the RN reduces with increased inhibitor concentration while both the I.E and Θ increase with increasing concentration of the extracts. This indicated that the CR of AISI 1007 steel in HCl solution decreases as the extract concentration increases which is in line with the weight loss result.

Figure 6 shows the variation of temperature of the solution against the time of exposure. It revealed that the solution without inhibitor has the highest maximum temperature

which could be due to more corrosion reaction in the solution than those with inhibitors. As the concentration of the inhibitor increases, the maximum temperature reached in the solutions decreases which might be due to retarded corrosion activities by the inhibitors.

To justify the utilization of the extracts of *Jatropha curcas* and *Moringa oleifera* as hybrid corrosion inhibitor on metal in HCl environment, this study compared the corrosion inhibition efficiency obtained in this study with that of other studies that used the extract of *Moringa oleifera* and *Jatropha curcas* singly and separately in acidic environment on mild steel. The maximum IE obtained in this study was 96% where the hybrid extracts were used while the range of IE values obtained from previous studies that used each of the extract was between 78 and 98.42% [6, 18, 28, 37–49]. The IEs of some extracts are presented in Table 4 which were compared with this present study. This indicates that the combination of the two extracts showed superior corrosion inhibiting activities than the single extract. This could be linked to the complementary phytochemicals present in both extracts as pointed out in Table 2. More so, the number of phytochemicals present when the hybrid extracts were used could have increase; hence, aiding the improvement of inhibiting corrosion by quick formation of barriers against corrosion in the HCl environment. The passive film formation serves as a protective shield between the substrate and corrosion media surface by stifling the corrosion reactions processes between the anodic oxidation and cathodic reduction. More so, the diverse constituents in the combined extracts can provide more stable film which are adherent on the substrate's surface. This causes hinderance to active corrosion reactions as well as impede $Cl^-$ reaction species penetration via the surface film barrier. The harmonious actions/reactions of these hybrid extract from *Moringa oleifera* and *Jatropha curcas* on the AISI 1007 steel surface by hindering $Cl^-$ species through the promotion of the formation of more stable inactive film on the substrate's surface by stifling and inhibiting corrosion reactions on the steel surface in the corrosive environment [35].

**Table 4** Inhibition efficiency of various green inhibitors used in previous studies compared with the hybrid used in this study

| S/N | Inhibitors | Environment | I.E(%) | Reference |
|---|---|---|---|---|
| 1 | Borage flower | HCl | 91.00 | [42] |
| 2 | Rice straw extract | $HCl/H_2SO_4$ | 85.00 | [43] |
| 3 | *Glycyrrhiza glabra* | $HCl/H_2SO_4$ | 88.00 | [44] |
| 4. | Lemon balm extracts | $H_2SO_4$ | 94.60 | [45] |
| 5. | *Ficus religiose* | $H_2SO_4$ | 88.29 | [46] |
| 6 | Nutmeg fruit | HCl | 87.81 | [47] |
| 7. | Sunflower seed hull | $HCl/H_2SO_4$ | 98.46 | [48] |
| 8. | Rosa canina fruit | HCl | 85.70 | [49] |
| 9 | Hybrid of *Jatropha curcas* and *Moringa oleifera* | HCl | 96.00 | Present study |

## 4 Conclusions

Corrosion control of AISI 1007 steel using hybrid inhibitors of plant extracts was investigated in this study. From the study, certain phytochemical constituents that are complementary for corrosion inhibition were discovered in the extracts of *Jatropha curcas* and *Moringa* oleifera such as alkaloids, tannins, flavonoids, saponins, and so on. The weight loss reduced with increased inhibitor concentration but increased with time of exposure. More so, the corrosion rate gradually decreases with time of exposure and the concentration of the inhibitor. The I.E (%) revealed physical adsorption mechanism since I.E increases with concentration of inhibitor. The hybrid inhibitor led to the occurrence of quicker activation of passivity level on the surface of the substrate. The maximum inhibition efficiency in this study was 96%. Hence, the utilization of the hybrid extract was able to inhibit corrosion on AISI 1007 steel on a quicker level compared to single usage of the extract. Equal mixture of *Moringa oleifera* and *Jatropha curcas* leaves extract served as good inhibitors for the corrosion of AISI 1007 steel in HCl solution.

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**Data Availability** Data associated with the manuscript are available on request from the authors.

## Declarations

**Conflict of interest** The authors have no relevant financial or non-financial interests to disclose.

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