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Comparative Corrosion Behaviour of Mild Steel and Stainless Steel in Hydrochloric and Nitric Acid Environments: Implications for Sustainable Material Use

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ABSTRACT. Corrosion of structural metals in acidic environments remains a critical concern for both industrial efficiency and environmental sustainability. This study comparatively investigates the corrosion behaviour of mild steel and stainless steel in hydrochloric acid (HCl) and nitric acid (HNO_3) media at varying concentrations and immersion periods. Weight loss measurements were used to evaluate corrosion rates, supported by comparative analysis over a five-day exposure. The results revealed that corrosion rates increased with acid concentration and exposure time where HNO_3 showing stronger corrosive aggressiveness than HCl due to its oxidizing properties. Mild steel experienced significantly higher mass loss than stainless steel due to the absence of a stable passive oxide layer. A gradual reduction in corrosion rate after prolonged exposure indicated the formation of protective corrosion products that limit further dissolution. Overall, stainless steel demonstrated superior corrosion resistance under all conditions. These findings are vital for material selection in chemical and process industries, particularly where equipment is exposed to acidic effluents. Minimizing corrosion-related failures not only extends the service life of metallic components but also reduces environmental contamination and conserves metallic bioresources through more sustainable industrial practices.

Key words: Corrosion behavior, Acidic environment, Mild steel, Stainless steel, Weight loss analysis.

1. INTRODUCTION

Corrosion is a major challenge that engineers and scientists need to address to prevent damage to structures, chemical plants and metal objects. If left unchecked, it can cause not only economic losses but also environmental harm and risks to human safety (Malaret & Yang, 2022). The global iron and steel industry plays a significant role in boosting the gross domestic product (GDP) worldwide, particularly in developing countries (Cheng et al., 2020). This states that corrosion is a natural process that leads to the deterioration of materials particularly metals due to the environmental interactions and ultimately include the consequences of economic losses and industrial structural failures.

Mild steel and stainless steel are classified as ferrous metals because its contain high percentage of iron (Fe). The carbon steels are essentially iron-carbon alloys. This carbon steel are subdivided by the broad range of carbon content

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which included (a) mild or low carbon steel (0.08-0.30% carbon) (b) medium carbon steel (0.3-0.5% carbon) and (c) high carbon steel (0.55-1.40% carbon). Stainless steel are less likely to corrode as it contains chromium which form a protective oxide layers that enhances its resistance to corrosion.The API-grade carbon steels are the most dominant material used by different industries, especially in oil wells and gas transportation field due to their low cost, durability and mechanical efficiency. However, due to the long term exposure to continuous environment during various cleaning processes, the steel can be seriously corroded, leading to the deterioration of its surface and resulting in serious economic losses and environmental issues (Khamaysa et al., 2021; Rana & Jindal, 2024).

Mild steel is a metal which is commonly used in industrials and manufacturing of equipment for most industries round the world. It is cheaper cost compared with the other metals and its durable, hard and easy-to-wear physical properties make it a major choice in the manufacture of equipment parts. The main problem through the uses of mild steel in industry is its resistance against corrosion, especially in acidic solutions. This case led to raise the cost of maintenance of equipment that used mild steel and as a result increased costs for the company (Habeeb et al., 2018). In industrial environments metals are frequently exposed to bases or acids. As a metals subjected to such extreme conditions may change their properties that may ultimately result in the material's premature breakdown in service due to corrosion. By dissociating in the galvanic cell powerful acids like hydrochloric acid (HCl) and nitirc acid (HNO_3) speed up the corrosion rate of metals (Mohammed et al., 2023). Corrosion only takes place in specific environments which may be damp wet or dry. Environment in corrosion studies include concentration, pH, temperature, atmosphere, sea water, chemical, and fused salts (Widyanto et al., 2019). During corrosion, the kinetic of the cathodic and anodic partials reaction controls the rate of overall corrosion reaction (Husaini et al., 2018). To sum up, metals in contact with acidic conditions, like HCl and HNO_3, are easily prone to faster corrosion because of the separation of ions in the acids that promote galvanic cell reactions.

Scarce research has been conducted to determine corrosion behavior of metals in acidic environments; however, little has been published concerning the corrosion behavior of mild steel in mixed acid solutions in HCl and HNO_3 solutions. The objective of this study is to comparatively evaluate the corrosion behaviour of mild steel and stainless steel in HCl and HNO_3 media, with the aim of understanding their degradation characteristics in environmentally aggressive conditions. The findings are intended to support sustainable material selection and maintenance strategies in industries handling corrosive wastes or chemical by-products, thereby minimizing metal wastage, reducing environmental contamination from corroded metals and conserving metallic bioresources through improved corrosion management practices.

2. METHODOLOGY

2.1 Materials and Apparatus

The materials and apparatus used in this study were mild steel coupons (2 cm x 2 cm), stainless steel coupons (2 cm x 2 cm), different grades of emery paper (500 and 1000), vials, four-decimal analytical balance, beaker, measuring cylinder, distilled water and acetone.

2.2 Preparation of Acid Media

Different acid media were used this study consists of hydrochloric acid (HCl) and nitric acid (HNO_3). The concentrated acid solutions were diluted with distilled water to prepare test solutions at different concentrations such as 3.0 M, 2.0 M, 1.5 M, 1.0 M, 0.8 M and 0.5 M.

2.3 Surface Pre-treatment

Metal surface were polished with different grades of emery (500 and 1000). After that the mild steel and stainless steel coupons were cleaned in acetone solution followed by distilled water to remove any surface contaminations. Then, the cleaned coupons were dried and stored in desiccator until further use.

2.4 Corrosion Analysis

The mild steel and stainless steel coupons were weighed prior to the immersion in acidic solution using a analytical balance. Each coupon was then placed in vial with properly labeled as shown in Figure 1.

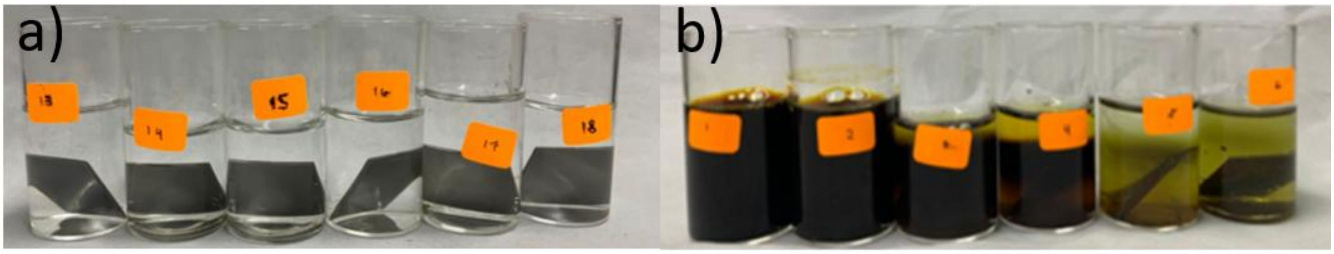

Figure 1. Stainless Steel (a) and Mild Steel Coupons Immersed in HNO_3 Solution at Various Concentrations

All the coupons were taken off after 1 day immersion and dried and reweighed using the same analtyical balance. This procedure was repeated daily for the five consecutive days. Then, the average weight loss for each cuopons was calculated and corrosion rate of the coupons was determined using this Equation 1 :

$$\text{Corrosion Rate(CR)} = \frac{\text{Weight Loss (g)} \,.\, \text{K}}{\text{Alloy Density (g/cm3)}.\,\text{Expsosed Area (A)}.\,\text{Exposure Time (hr)}} \quad (1)$$

Density of steel: 7.86 g/cm^3 , Density of Stainless Steel : 7.0 g/cm^3 (depending on the type of stainless steel).

3. RESULTS AND DISCUSSION

The corrosion behaviour of mild steel and stainless steel in HCl and HNO_3 solutions was evaluated based on the weight loss measurements presented in Tables 1 and 2. The results demonstrate that the corrosion rate increases proportionally with acid concentration and immersion time, consistent with the enhanced chemical reactivity and ionic dissociation of the acids. This trend agrees with previous findings that reported a positive correlation between acid molarity and corrosion rate due to increased hydrogen ion activity and metal dissolution kinetics (Mohammed et al., 2023; Widyanto & Putri, 2019). Furthermore, the higher aggressiveness of HNO_3 compared to HCl is attributed to its strong oxidizing nature, which accelerates the formation of soluble iron nitrate species, as similarly observed by Raschman et al. (2024). These observations indicate that nitric acid induces more extensive surface degradation, while hydrochloric acid promotes localized attack through chloride ion penetration, aligning with the typical electrochemical corrosion mechanism in acidic media.

Table 1. Weight Loss of Mild Steel in Different Acid Solutions at Various Concentrations

Solution	Concentration (M)	Weight Loss (g)				
		1st day	2nd day	3rd day	4th day	5th day
HNO_3	3.0 M	0.104	0.198	0.283	0.413	0.477
	2.0 M	0.176	0.328	0.503	0.713	0.767
	1.5 M	0.261	0.463	0.686	0.922	1.397
	1.0 M	0.214	0.395	0.630	0.835	1.106
	0.8 M	0.298	0.534	0.785	1.107	1.443
	0.5 M	0.550	0.947	1.459	1.963	2.511
HCl	3.0 M	0.010	0.013	0.021	0.029	0.032
	2.0 M	0.010	0.020	0.034	0.041	0.041
	1.5 M	0.011	0.036	0.043	0.046	0.051
	1.0 M	0.010	0.038	0.048	0.052	0.055
	0.8 M	0.011	0.056	0.068	0.072	0.089
	0.5 M	0.010	0.061	0.082	0.100	0.130

Table 2. Weight Loss of Stainless Steel in Different Acid Solutions at Various Concentrations

Solution	Concentration (M)	Weight Loss (g)				
		1st day	2nd day	3rd day	4th day	5th day
HNO_3	3.0 M	0.001	0.005	0.009	0.010	0.012
	2.0 M	0.001	0.007	0.011	0.014	0.015
	1.5 M	0.001	0.009	0.015	0.016	0.018
	1.0 M	0.001	0.011	0.020	0.020	0.022
	0.8 M	0.002	0.018	0.025	0.028	0.028
	0.5 M	0.002	0.022	0.028	0.034	0.050
HCl	3.0 M	0.000	0.000	0.000	0.000	0.001
	2.0 M	0.000	0.001	0.001	0.001	0.002
	1.5 M	0.000	0.001	0.002	0.002	0.003
	1.0 M	0.000	0.001	0.002	0.003	0.004
	0.8 M	0.000	0.002	0.003	0.004	0.005
	0.5 M	0.000	0.003	0.0045	0.006	0.006

Figure 2 illustrates the variation of weight loss of mild steel and stainless steel with immersion time and acid concentration. A progressive increase in weight loss was observed for both metals, indicating that corrosion is time-dependent and strongly influenced by acid strength. The acceleration of metal dissolution with increasing concentration can be explained by higher hydrogen ion activity and the enhanced diffusion of oxidizing species at the metal–solution interface (Malaret & Yang, 2022; Mohammed et al., 2023). The nonlinear trends observed in Figure 2 suggest that corrosion does not proceed uniformly across the surface but involves localized electrochemical reactions and the formation of transient corrosion products consistent with previous findings on heterogeneous corrosion mechanisms in acidic environments (Othman et al., 2025). These results collectively confirm that both acid concentration and exposure time play critical roles in controlling the kinetics and morphology of metal degradation. In Figures 3, a presentation of the corrosion rates of mild steel and high carbon steel has been given respectively in these acid media over an exposure period of five days (Day 1-Day 5). The corrosion rates of the mild steel and stainless-steel coupons were identified using expressed equation 1 previously.

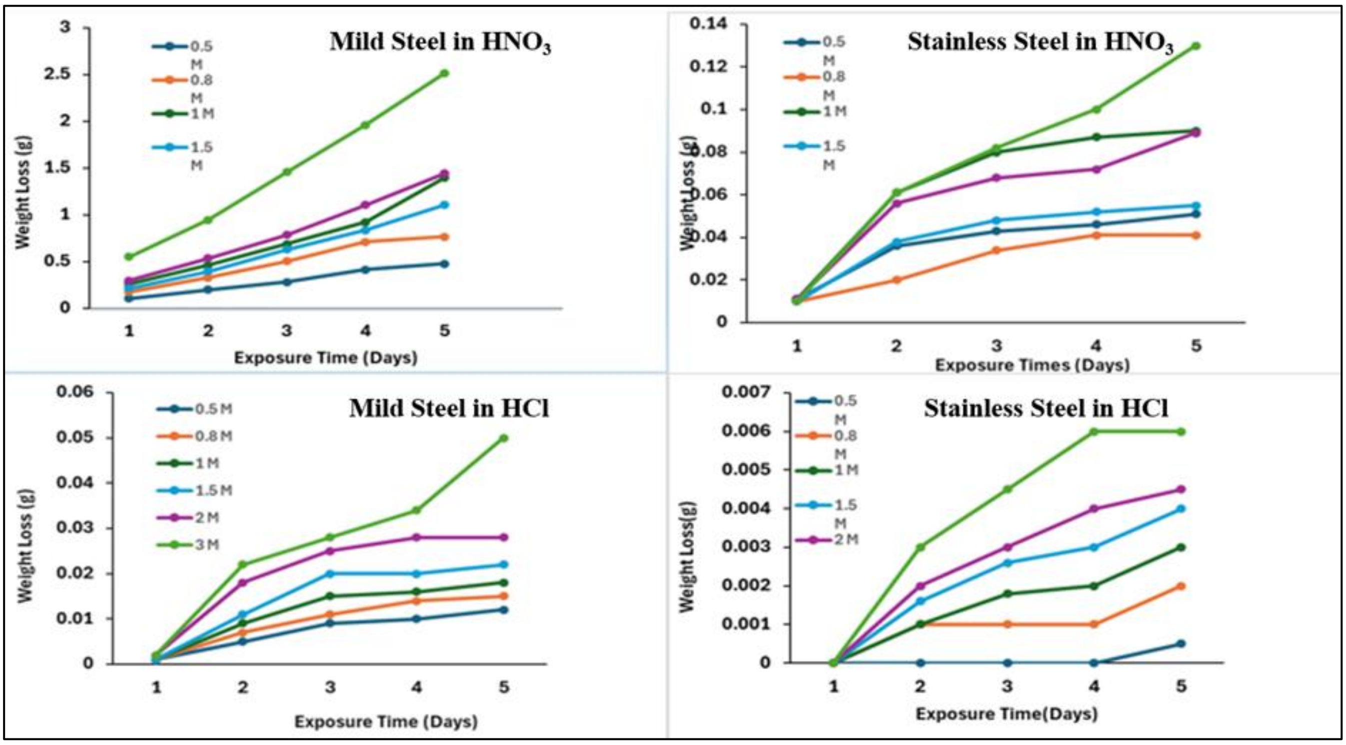

Figure 2. Variation of weight loss (g) with time (days) for mild steel and stainless steel in different concentrations of HCl and HNO_3 Solution

The figure shows that the corrosion rate of both metals was the highest in nitric acid medium, followed by hydrochloric acid. The higher corrosion rate in HNO_3 is due to its strong oxidizing nature, which enhances the dissolution of iron and promotes continuous metal degradation. On the other hand, although HCl is also aggressive, it mainly causes localized attack through the penetration of chloride ions into the protective oxide layer on the metal surface. This behaviour leads to pitting and uneven corrosion across the surface. The corrosion process in nitric acid generally follows an autocatalytic mechanism, where the displacement of hydrogen ions is followed by the reduction of HNO_3 instead of hydrogen evolution, resulting in the formation of $Fe(NO_3)_2$ and nitrogen dioxide as shown in Equation (2).

$$Fe + 4HNO_3 \rightarrow Fe(NO_3)_2 + 2H_2O + 2NO_2 \qquad (2)$$

The evolution of NO_2 gas gives the solution a brownish colour, confirming the reduction of nitric acid and the oxidation of the metal. The corrosion rate of mild steel in all acidic media was higher than that of stainless steel. This finding agrees with previous reports by Muhammad et al. (2024), stating that the carbon content has minimal effect on corrosion resistance, while the chromium present in stainless steel forms a passive film that improves its stability in aggressive environments.

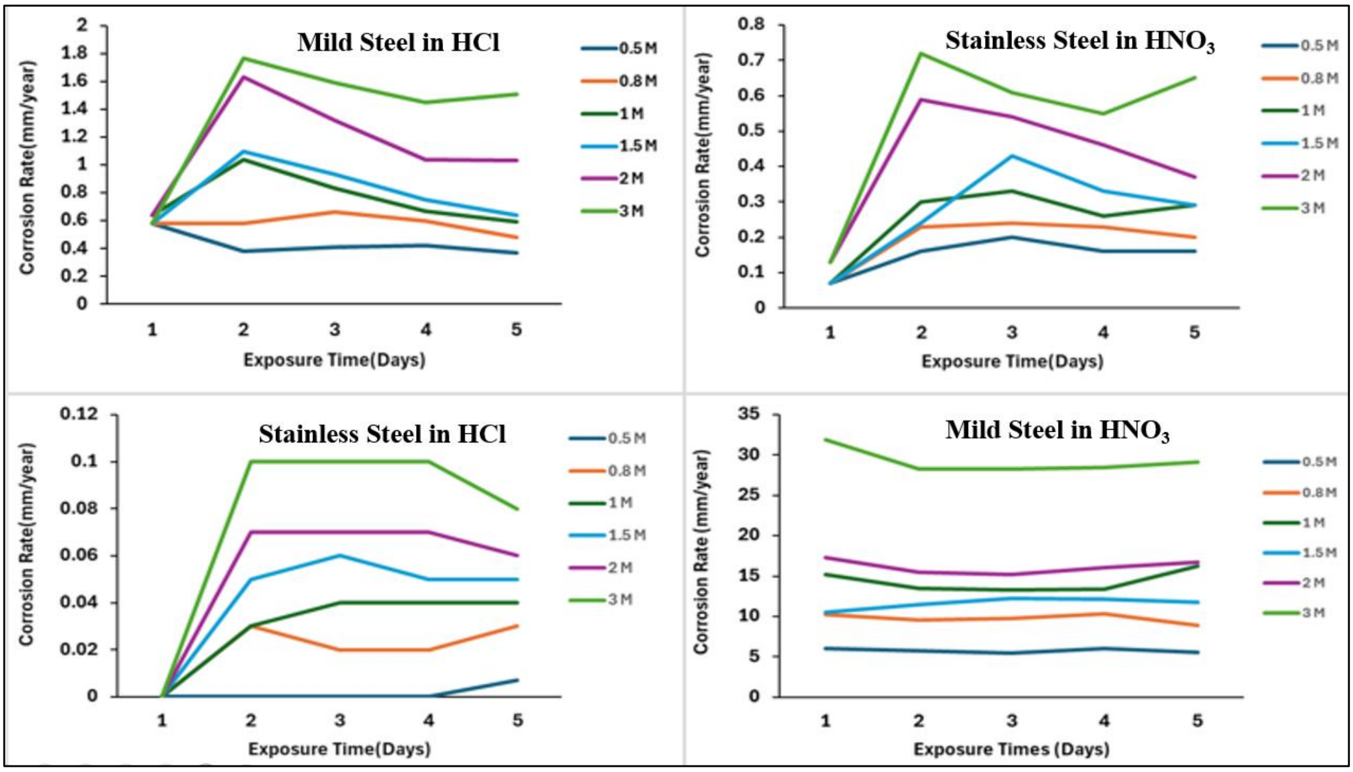

Figure 3. Variation of Corrosion Rate (mm/year) with Exposure time (days) of Mild Steel and Stainless Steel in Different Concentrations of HCl and HNO_3 Solution

The corrosion behaviour observed after the third day indicates a gradual decline in corrosion rate for both metals and this reduction attributed to the development of surface films composed of corrosion products that partially inhibit further dissolution. Such passivation behaviour is typical for ferrous alloys in acidic environments once oxide or hydroxide layers begin to form, limiting active metal exposure to the electrolyte (Shen et al., 2024). The stabilization of corrosion rate with time may also result from the consumption of reactive species and the decreased diffusion of hydrogen and nitrate ions through the corrosion film (Widyanto & Putri, 2019). Stainless steel exhibits stronger passivation due to its chromium-based oxide barrier, while mild steel shows only partial film protection, explaining its continued but slower mass loss. These findings confirm that extended exposure leads to quasi-steady corrosion kinetics dominated by passive-film formation rather than active metal dissolution (Wang et al., 2024).

4. CONCLUSION

The findings of this study revealed that the corrosion behaviour of mild steel and stainless steel is highly dependent on the type and concentration of acidic medium. Nitric acid exhibited the highest corrosion activity due to its strong oxidizing ability, which enhances metal dissolution, whereas hydrochloric acid caused localized corrosion through chloride ion penetration. Mild steel showed a higher corrosion rate than stainless steel because it lacks a stable chromium oxide layer that provides surface passivation. The increase in corrosion rate with immersion time and acid molarity indicates that metal degradation is strongly governed by the chemical reactivity and concentration of the solution. Overall, stainless steel demonstrated superior corrosion resistance in both acidic environments, confirming its suitability for industrial applications involving aggressive media and its contribution to reducing material loss, maintenance cost, and environmental contamination.

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AUTHOR CONTRIBUTIONS
Experimental Analysis: Muhammad Syakir Zukfli, Muhammad Nur Aidid Farihin Kashpu Anuar, Danish Haiqal Umar Dzakir, Adam Harith Noorzulan, Che Muhammad Amin Che Hamid & Ahmad Ifwad Mohamed; Writing - review and editing; Nazhirah Muhammad Nasri & Mohammad Hafizudden Mohd Zaki. All authors have read and agreed to published version of the manuscript.

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Not applicable.

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