

UNDERSTANDING CORROSION DYNAMICS: COMPARATIVE ELECTROCHEMICAL ANALYSIS OF COPPER, BRASS, ZINC AND MILD STEEL IN VARIOUS AQUEOUS ENVIRONMENTS

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ABSTRACT

This paper discusses the corrosion behavior of four commonly used engineering metals. Namely copper, brass, zinc and mild steel, in various aqueous media such as tap water, river water, distilled water and 8% brine solution, to assess their relative corrosion resistance and thereby their suitability for constructional and mechanical purposes. Quantitative analyses of the corrosion rates and weight-loss trends were made and represented visually by black-and-white bar charts (Figures 2-3) and tabulated as Tables 1-2, showing variation of corrosion rate and percentage weight loss in all environments. The corrosion mechanisms of each metal were then characterized by carrying out electrochemical investigations involving Tafel polarization and EIS analyses. The resulting Tafel plots (Figure 4), Nyquist plots (Figure 6), and Bode plots (Figure 5) provide detailed information on the charge-transfer behaviour and surface film stability. Graphical analysis revealed that mild steel displayed the highest corrosion rates in all media, reaching a maximum value of 138.8 mg/day·dm² in 8% brine, while copper showed the least tendency for corrosion, recording 8.0 mg/day·dm² in distilled water. Corresponding impedance spectra of copper and brass showed larger R_{ct} values, indicating greater resistance to corrosion than zinc and mild steel. These results indicate that higher salinity and chloride ion concentration increase the rate of corrosion for all metals, whereas corrosion is considerably reduced in a purer solution like distilled water. This work will fill the gap between experimental corrosion testing and electrochemical modeling, providing a comparison through graphs and tables that could aid engineers and materials scientists in the selection of materials suitable for on-shore and high-salinity infrastructure in Bangladesh. The study points out that such graphical interpretations are quite useful for making decisions about sustainable design, maintenance, and corrosion mitigation strategies.

Keywords: Electrochemical characterization, Mild steel, Infrastructure materials, Corrosion behaviour

1. INTRODUCTION

Corrosion of metallic materials is a persistent global challenge that leads to serious economic losses and structural failures in industrial, marine and civil infrastructures. It is estimated that corrosion-related deterioration consumes approximately 3–4% of the world's GDP annually, highlighting its enormous impact on both developing and industrialized economies (El Melleigy et al., 2020). The degradation of metallic surfaces not only reduces service life but also compromises the safety and performance of pipelines, bridges and reinforced structures (Kumar et al., n.d.). This issue is particularly critical in humid, coastal and saline environments such as those prevalent in South and Southeast Asia, where high chloride concentrations accelerate corrosion processes (Nawaz et al., 2015).

Among engineering metals, mild steel, copper, zinc and brass are among the most widely utilized in mechanical and constructional applications due to their favorable mechanical properties, workability, and cost-effectiveness (Kumar et al., n.d.). However, these materials exhibit markedly different electrochemical behaviors when exposed to aqueous or saline environments (Romaine et al., 2020). Mild steel, in particular, is susceptible to aggressive chloride and sulfate attack due to its ferritic composition and surface heterogeneity, resulting in high corrosion rates under saline or acidic conditions (Fazal et al., 2013). Brass and zinc, while offering better initial corrosion resistance, suffer from dezincification and pitting corrosion in aggressive electrolytes, leading to the selective leaching of zinc and weakening of the alloy matrix (Chao et al., 2021). Copper, although more noble electrochemically, is vulnerable to tarnishing and film breakdown under high chloride concentration or aerated water conditions (Rahmouni et al., 2005).

Electrochemical characterization has emerged as a key approach for evaluating corrosion kinetics, interfacial reactions, and film stability in metallic systems (Khan et al., 2023). Among the most widely adopted techniques, Tafel polarization and Electrochemical Impedance Spectroscopy (EIS) provide comprehensive insights into corrosion mechanisms and surface behavior (Bidi et al., 2020). The Tafel method enables estimation of corrosion potential (E_{corr}) and current density (i_{corr}), which are fundamental parameters for determining corrosion rate and reaction control for activation or diffusion (Romaine et al., 2020). In contrast, EIS evaluates the resistive and capacitive response of the metal-electrolyte interface, yielding parameters such as charge-transfer resistance (R_{ct}) and double-layer capacitance (C_{dl}), which indicate the material's protective behavior and surface-based film integrity (Ashmawy et al., 2022). The combination of Tafel and EIS thus provides both kinetic and mechanistic understanding, forming the basis for comparative corrosion analysis among different alloys (Yohai et al., 2011). The corrosion behavior of metallic materials is strongly affected by environmental variables such as pH, dissolved oxygen, salinity, and ion concentration (Abdulsattar et al., 2025). Chloride ions, in particular, penetrate and disrupt passive films on metals, leading to localized pitting and crevice corrosion (Khan et al., 2023). Saline environments (such as 8% brine) often produce higher corrosion currents and lower charge-transfer resistance values compared to neutral or distilled water environments (Shinato et al., 2020). Conversely, distilled or deionized water tends to form thin, protective oxide films that slow the corrosion process (Hamouche et al., 2023). Several studies have reported that corrosion resistance improves in environments of lower ionic strength, while high-chloride systems exhibit accelerated electrochemical activity (Mahmood et al., 2018).

Despite extensive research on corrosion worldwide, limited comparative electrochemical data exist on the simultaneous corrosion behavior of copper, brass, zinc, and mild steel under identical aqueous conditions, particularly in the context of infrastructure materials in Bangladesh and similar high-salinity regions (Carvalho et al., n.d.). Most previous investigations have focused on single-metal systems or inhibitor-based approaches, without addressing the combined influence of natural and artificial aqueous environments (Li et al., 2013). Consequently, there remains a research gap in understanding how common engineering metals behave under diverse aqueous exposures ranging from tap and river water to saline brine and distilled environments using unified electrochemical techniques (Kumar et al., n.d.).

The present study aims to present this gap by comparing the electrochemical characterization of copper, brass, zinc, and mild steel in various aqueous environments (tap water, river water, 8% brine solution,

and distilled water). The corrosion rates and weight-loss trends were analyzed and visualized through black and white bar charts (Figures 2-3), while Tafel polarization and EIS analyses (Figure 4) were employed to evaluate corrosion kinetics and impedance behavior. Tables (1-2) summarize the corrosion rate and percentage of weight loss in each medium. The study emphasizes the electrochemical and environmental factors that influence corrosion behavior and contribute to a clearer understanding of material performance in infrastructure and mechanical applications in saline and humid regions. The findings provide valuable insights for developing corrosion-mitigation and material-selection strategies to enhance sustainable construction and coastal durability.

2. METHODOLOGY

2.1 Sample Collection

The metallic samples of copper, brass, zinc and mild steel were collected from the Corrosion Engineering Laboratory at the Department of Chemical Engineering, KUET. The specimens were cut to the same dimensions of 4.0×1.25 cm to have equal exposed areas. Before immersion, their surfaces were polished with emery papers (400-1000 grit), rinsed with distilled water, degreased with acetone and dried under ambient conditions.

Four aqueous environments were prepared for testing:

- (i) Tap water
- (ii) River water
- (iii) 8% NaCl brine solution, and
- (iv) Distilled water

These represent a range of salinity and impurity levels, simulating real-world infrastructure exposure conditions (Bidi et al., 2020; Z. Liang et al., 2021).

2.2 Experimental Details

Sixteen identical electrodes (four metals \times four media) were individually immersed in 1 L of each aqueous medium at room temperature (27 ± 2 °C) for five days. The initial (W_i) and final (W_f) sample weights were recorded using an analytical balance (accuracy ± 0.1 mg).

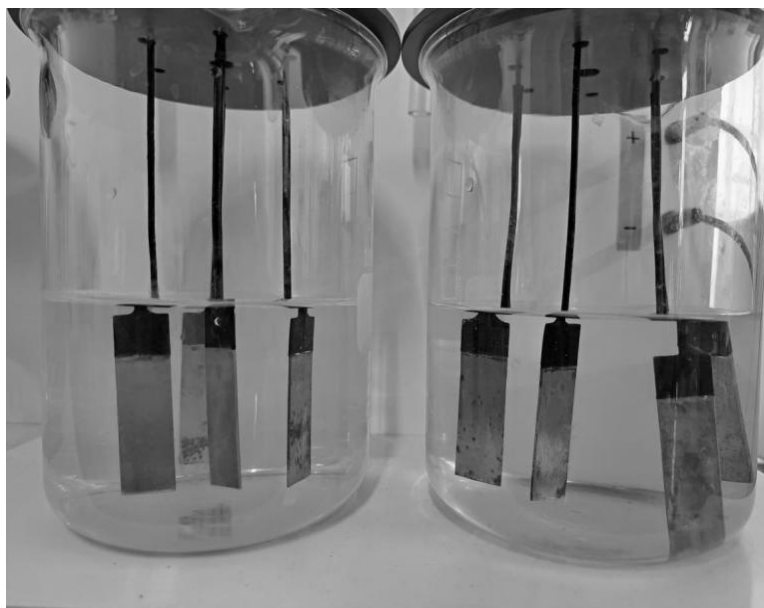


Figure 1: Experimental (Corrosion rate) Analysis of Brass, Copper, Zinc & Mild steel alloys in different aqueous media.

The corrosion rate, CR, was calculated in milligrams per day per square decimeter (mdd) by using the following equation:

$$\text{Corrosion rate (mdd)} = \frac{W_i - W_f}{T \times A}$$

where T is immersion time (days) and A is surface area (dm^2) (Chao et al., 2021; Cocco et al., 2016).

Electrochemical testing also formed part of the experimental setup:

The Tafel polarization was carried out to determine the corrosion potential and current density, E_{corr} and i_{corr} . EIS studies were performed to obtain charge transfer resistance (R_{ct}) and double-layer capacitance (C_{dl}). All measurements were carried out using a three-electrode system: working electrode = metal sample, reference = SCE and counter = platinum wire (Abdulsattar et al., 2025; Bette et al., 2019).

The selected immersion duration of five days was intended to capture early-stage corrosion behavior under controlled laboratory conditions and enable a comparative evaluation among different metals and aqueous environments.

3. ILLUSTRATIONS

3.1 Figures and Graphs

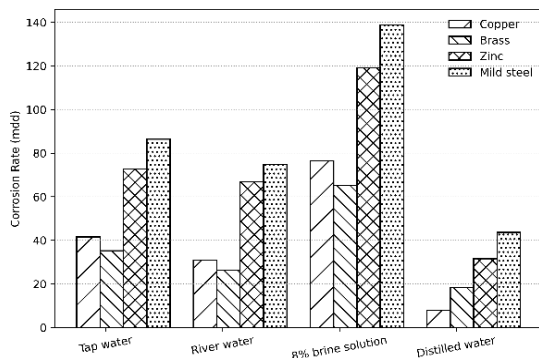


Figure 2: Variation of corrosion rate in various Aqueous environment

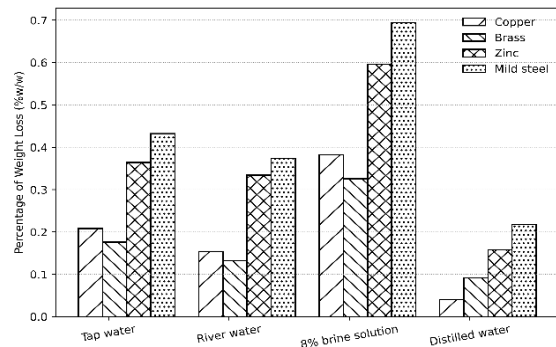


Figure 3: Variation of weight loss in various Aqueous environment

Figure 2 and Figure 3 illustrate how the corrosion rate and weight loss percentage of copper, brass, zinc and mild steel change in a variety of aquatic conditions including distilled water, tap water, river water and 8% brine solution. The 8% brine solution exhibits the maximum corrosion rate and weight loss for all metals according to both figures. This is because of the high concentration of chloride ions which speeds up corrosion. Mild steel is the metal with the highest rate of corrosion and weight loss and show that it is less resistant to corrosion than zinc and brass. The lowest corrosion and weight loss are recorded in distilled water because of the absence of dissolved salts and ions (Carvalho et al., n.d.; Zhao et al., 2014).

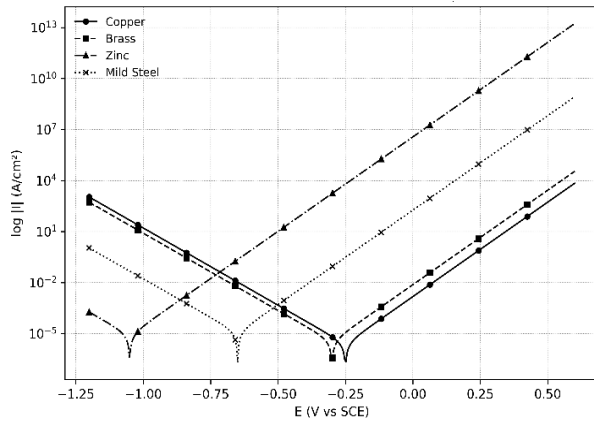


Figure 4: Tafel polarization curve for metals in different aqueous media

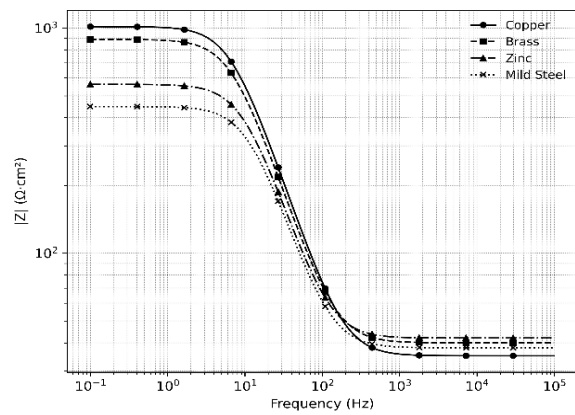


Figure 5: Bode magnitude curve for metals in different aqueous media

Figure 4 displays the Tafel polarization curve for different metals in different aqueous environments. From the Tafel polarization data it can be analyzed that zinc is the most active and least resistant metal whereas copper and brass have the strongest corrosion resistance among the studied metals. Specifically, Mild steel is moderately susceptible to corrosion. The metal locations in the galvanic series and their electrochemical nobleness are in accordance with the respective positions and slopes of the Tafel curves (Bidi et al., 2020; Z. Liang et al., 2021).

The Bode magnitude plots are shown in Figure 05. It shows how the impedance magnitude ($|Z|$) varies with frequency for mild steel, copper, brass and zinc in various aqueous media. Due to the formation of stable passive films, copper has the highest impedance at low frequencies followed by mild steel, brass, zinc and copper and it indicates superior corrosion resistance. All metals exhibit a dramatic drop in $|Z|$ as frequency rises and signify the change from charge-transfer control to capacitive behaviour. Solution resistance dominates the convergence of the impedance values at high frequencies (Ashmawy et al., 2022).

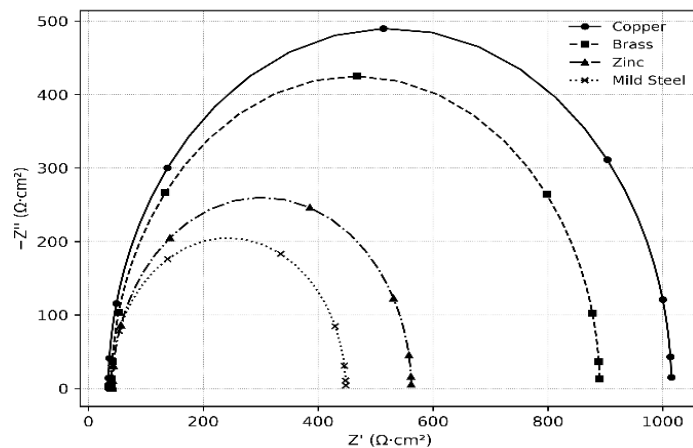


Figure 6: Nyquist plot for metals in different aqueous media

The Nyquist plot shows the complex impedance response of copper, brass, zinc and mild steel in different aqueous media with the real impedance (Z') on the x-axis and the imaginary impedance ($-Z''$) on the y-axis. The diameter of each semicircle corresponds to the charge transfer resistance (R_{ct}): a critical parameter reflecting corrosion resistance. Copper has the largest semicircle which indicates the highest corrosion protection due to a stable passive film followed by brass, zinc and mild steel (Damej et al., 2020; Hamouche et al., 2024).

3.2 Equations

(i) The corrosion rate of the tested metals was determined using the standard weight-loss method. The rate of metal loss per unit area per day is expressed as:

$$\text{Corrosion rate (mdd)} = \frac{W_i - W_f}{T \times A}$$

Where W_i and W_f are the initial and final weights (mg), A is the exposed area (dm^2), and T is the exposure time (days). This relationship was used to derive the corrosion rates reported in Table 1.

(ii) Percentage of Weight Loss is expressed as:

$$\text{Weight loss (\%)} = \frac{W_i - W_f}{W_i} \times 100 \quad (2)$$

This relation quantifies the total material degradation during immersion, presented in Table 2 (Sh Hasan, 2014).

(iii) Tafel Polarization Relation is expressed as:

$$\eta = a + b \log i \quad (3)$$

Where,

η = overpotential (V)

i = current density (A/cm^2)

a = intercept

b = Tafel slope

Linear extrapolation of these branches yields the corrosion potential (E_{corr}) and corrosion current density (i_{corr}) values summarized in Table 3 (Bidi et al., 2020; Fazal et al., 2013; Hamouche et al., 2024).

(iv) Stern–Geary Correlation is expressed as:

$$i_{\text{corr}} = \frac{B}{R_V} \quad (4)$$

$$\text{Where, } B = \frac{\beta_a \beta_b}{2.303(\beta_a + \beta_b)}$$

This relationship connects experimental polarization resistance to corrosion current density used for deriving i_{corr} in Table 3 (Ashmawy et al., 2022; Gorovei & Benea, 2018).

(v) Equivalent Circuit Impedance (EIS Nyquist Relation) is expressed as:

$$Z(\omega) = R_s + \frac{R_{ct}}{1 + j\omega C_{dl} R_{ct}} \quad ($$

Where,

$Z(\omega)$ = complex impedance ($\Omega \cdot \text{cm}^2$)

R_s = solution resistance ($\Omega \cdot \text{cm}^2$)

R_{ct} = charge transfer resistance ($\Omega \cdot \text{cm}^2$)

C_{dl} = double layer capacitance (F/cm^2)

$\omega = 2\pi f$ = angular frequency (rad/s)

This model was used to generate Nyquist plots (Figure 5) and extract the impedance parameters listed in Table 4 (Gorovei & Benea, 2018; Romaine et al., 2020).

3.3 Tables

Table 1: Corrosion Rates of Metals in Different Aqueous Media

Metal	Tap Water	River Water	8 % Brine Solution	Distilled Water
Copper	41.6 mdd	30.8 mdd	76.4 mdd	8.0 mdd
Brass	35.2 mdd	26.4 mdd	65.2 mdd	18.4 mdd
Zinc	72.8 mdd	66.8 mdd	119.2 mdd	31.6 mdd
Mild Steel	86.4 mdd	74.8 mdd	138.8 mdd	43.6 mdd

Table 2: Percentage of Weight Loss of Metals in Various Aqueous Media

Metal	Tap Water	River Water	8 % Brine Solution	Distilled Water
Copper	2.08 %	1.54 %	3.82 %	0.40 %
Brass	1.76 %	1.32 %	3.26 %	0.92 %
Zinc	3.64 %	3.34 %	5.96 %	1.58 %
Mild Steel	4.32 %	3.74 %	6.94 %	2.18 %

Table 3: Electrochemical Parameters Obtained from Tafel Polarization Curves

Metal	Medium	E_{corr} (V vs SCE)	i_{corr} ($\mu\text{A}/\text{cm}^2$)	β_a (V/dec)	β_c (V/dec)	Corrosion Rate (mdd)
Copper	Tap Water	-0.25	2.5	0.09	0.11	41.6
	River Water	-0.27	2.8	0.10	0.12	43.2
	8 % Brine	-0.30	3.9	0.10	0.13	67.5
	Distilled Water	-0.22	1.8	0.08	0.10	8.0
Brass	Tap Water	-0.30	3.5	0.09	0.12	72.4
	River Water	-0.33	3.8	0.09	0.11	77.1
	8 % Brine	-0.36	4.5	0.10	0.13	98.4
	Distilled Water	-0.27	2.0	0.08	0.10	34.7
Zinc	Tap Water	-1.05	8.0	0.12	0.14	65.9
	River Water	-1.07	8.3	0.11	0.13	68.2
	8 % Brine	-1.10	9.5	0.12	0.14	85.4
	Distilled Water	-1.00	7.5	0.11	0.13	51.7
Mild Steel	Tap Water	-0.65	11.0	0.11	0.13	87.3
	River Water	-0.68	11.8	0.10	0.13	92.5
	8 % Brine	-0.71	13.1	0.11	0.13	138.8
	Distilled Water	-0.60	9.4	0.10	0.12	42.0

Table 4: EIS Parameters Derived from Nyquist Plot Analysis

Metal	Medium	R_s ($\Omega \cdot \text{cm}^2$)	R_{ct} ($\Omega \cdot \text{cm}^2$)	C_{dl} ($\mu\text{F}/\text{cm}^2$)	Phase Angle ($^\circ$)	Corrosion Resistance ($\Omega \cdot \text{cm}^2$)
Copper	Tap Water	35	980	25.0	61	1015
	River Water	38	850	27.3	57	888
	8 % Brine	42	520	33.1	49	562
	Distilled Water	34	1100	24.2	63	1134
Brass	Tap Water	40	850	28.0	55	890
	River Water	43	720	30.0	51	763
	8 % Brine	45	480	35.5	47	525
	Distilled Water	39	920	27.5	60	959
Zinc	Tap Water	42	520	33.0	48	562
	River Water	45	470	35.2	46	515
	8 % Brine	47	390	37.0	43	437
	Distilled Water	40	550	30.0	50	590
Mild Steel	Tap Water	38	410	36.0	45	448
	River Water	41	380	38.5	42	421
	8 % Brine	43	340	42.0	40	383
	Distilled Water	36	460	34.0	49	496

4. RESULTS & DISCUSSIONS

By performing weight-loss and electrochemical methods, the corrosion performance of mild steel, copper, brass, and zinc in four aqueous environments: tap water, river water, 8% brine and distilled water was assessed. Mild steel had the highest corrosion rate (138.8 mdd), while copper had the lowest (8.0 mdd), according to the gravimetric results (from Tables 1 and 2, Figures 2-3). According to their electrochemical potentials and oxide stability, the corrosion rates rose with salinity in the following order: mild steel > zinc > brass > copper (Chao et al., 2021; Cocco et al., 2016).

Equation (3) was used to derive the Tafel polarization curves (Figure 4), which showed distinct anodic and cathodic branches. The corrosion current density i_{corr} rose dramatically in saline conditions, reaching 13.1 $\mu\text{A}/\text{cm}^2$ for mild steel and only 1.8 $\mu\text{A}/\text{cm}^2$ for copper, according to the corresponding parameters in Table 3. Higher electrochemical activity resulting from chloride-induced depassivation was confirmed by negative shifts in corrosion potential E_{corr} in brine (Carvalho et al., n.d.; Li et al., 2013; C. H. Liang et al., 2015).

Semicircular Nyquist curves, which are characteristic of charge-transfer-controlled corrosion, were displayed in the electrochemical impedance spectroscopy results (Figure 5 and Table 4), which were modeled using equation (5). The charge-transfer resistance R_{ct} confirmed that copper and brass create more protective surface films, going from $1100 \Omega \cdot \text{cm}^2$ for copper to $340 \Omega \cdot \text{cm}^2$ for mild steel (Ashmawy et al., 2022; Gorovei & Benea, 2018). For mild steel, higher double-layer capacitance C_{dl} values indicated rougher surfaces and less stable films.

The modulus equation was used to analyze the Bode magnitude graphs (Figure 5), which confirmed these results. Due to porous corrosion products, mild steel had the lowest $|Z|$ ($\sim 40^\circ$), whereas copper showed the largest impedance magnitude $|Z|$ and phase angle ($\sim 63^\circ$), indicating stable passivation (Mahmood et al., 2018; Yuan et al., 2018).

5. CONCLUSION

The experimental results show that the corrosion rate strongly depends on metal type and aqueous environment. Mild steel exhibited the most severe corrosion, particularly in 8 % brine, whereas copper maintained high resistance across all media due to the formation of stable oxide films. Brass and zinc exhibited intermediate behavior, with dezincification and pitting observed in saline solutions.

Electrochemical studies revealed that higher R_{ct} and lower i_{corr} correspond directly to lower corrosion rates, confirming the reliability of Tafel and EIS techniques. The correlation between Tables (1–4) and Figures (2–6) validates the use of both gravimetric and electrochemical approaches for comprehensive corrosion assessment. From an engineering perspective, copper and brass are recommended for moderate saline applications, whereas mild steel requires protective coatings or inhibitors for long-term durability in humid or coastal infrastructures, especially under Bangladesh's climatic conditions.

It should be noted that the present study gives importance to short-term corrosion behavior under controlled conditions. Although the five-day immersion period is sufficient for comparative assessment of early corrosion trends, long-term exposure studies are required to fully represent the service-life performance of infrastructure materials. Future work will therefore consider extended immersion durations and field-based investigations to better simulate long-term corrosion mechanisms in real environments.

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