Stabilized Biofilm Analogues as Sustainable Corrosion-Resistant Coatings

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Abstract

This study tested whether a stabilized biofilm-inspired coating could protect steel from corrosion in harsh environments. Steel coupons were coated with a biofilm-analogue polymer film and exposed (for 4 weeks) to four conditions: artificial saltwater (3.5% NaCl), household vinegar (5% acetic acid), an oil–brine interface, and ambient laboratory air. Mass loss (in grams) were recorded for coated vs. uncoated coupons. Coated samples lost substantially less mass and had lower corrosion scores in saltwater, vinegar, and oil–brine environments, while ambient air caused minimal corrosion for both. For example, in saltwater the coated coupons lost only ~0.12 g on average versus ~0.37 g for uncoated. These results support the hypothesis that the biofilm-like coating acts as a protective barrier against corrosive agents. The findings align with prior reports that biofilms and cellulose layers can inhibit corrosion. This suggests biofilm-inspired coatings could be a green alternative to conventional anticorrosion treatments.

Introduction

Corrosion is one of the most damaging processes in materials science, costing **3–4% of the world's GDP annually** through infrastructure damage, equipment failure, and maintenance (Iannuzzi & Frankel, 2022). Conventional corrosion-control strategies such as chemical inhibitors, galvanization, and synthetic coatings are effective but come with significant drawbacks: they are expensive, environmentally harmful, or inefficient long term (Shekari, 2017). A new, eco-friendly alternative is emerging from microbiology: **biofilm-based corrosion inhibition**.

Biofilms, the slimy microbial communities that attach to surfaces, were once seen only as destructive. However, recent research has revealed their dual role: some biofilms actually **protect metals** by blocking corrosive agents, producing antimicrobial compounds, and secreting sticky polymers that mimic protective coatings. A 2021 study found that marine biofilms formed by *Tenacibaculum mesophilum* D-6, *T. litoreum* W-4, and *Bacillus* sp. Y-6 protected X80 carbon steel. Their secreted extracellular polymeric substances built adsorbed layers that significantly inhibited corrosion, as demonstrated by electrochemical tests and weight-loss measurements (Zhang, Liu & Chen, 2021).

For example, *Bacillus brevis* biofilm strain 18-3 produces **gramicidin S**, a cyclic decapeptide antibiotic that inhibits corrosion-causing **sulfate-reducing bacteria (SRB)**. Studies show that this biofilm can reduce mild steel corrosion rates **10–20 fold** compared to controls by preventing SRB and iron-oxidizing bacteria from colonizing the surface (Zuo, R., & Wood, T.

K., 2004). Similarly, *Bacillus licheniformis* biofilms generate **γ-polyglutamate**, a sticky polymer that creates a physical protective layer on aluminium achieved **90% corrosion inhibition of aluminium** (Sayahi, Saba & Al Disi, 2025). Even common antibiotics such as **ampicillin**, when applied before SRB colonization, have shown corrosion-inhibition effects in stainless steel reactors. Additionally, *Photobacterium sp.* 9-1 showed approximately **97% weight-loss reduction** on carbon steel surfaces during corrosion testing (Zhu, 2025). These findings suggest that **biofilm-derived peptides and polymers** can act as natural, green corrosion inhibitors.

This project matters because it bridges basic microbiology with applied corrosion engineering, exploring a low-cost, sustainable alternative to harsh chemical inhibitors. Several studies suggest that biopolymers such as γ-polyglutamate (γ-PGA) and surface-active peptides like Gramicidin S can alter metal surface chemistry and act as anti-corrosive agents by forming protective adsorbed layers or chelating corrosive ions (Zhu, 2025). In the long term, bioengineered microbes could even be designed to secrete such optimized corrosion-resistant peptides or polymers, offering a tailored biotechnological solution.

However, testing purified molecules or engineered strains requires advanced facilities and strict biosafety handling, which places them beyond the scope of this work. Instead, this project focuses on natural, food-safe biofilms and bio-derived coatings as a practical entry point. The outcomes here , such as the performance of alginate + algal biomass composites can provide valuable insight and groundwork for future studies that systematically evaluate γ-PGA, peptide-based coatings, or engineered microbial systems under controlled laboratory conditions.

Hypothesis

Preserved biofilm biomass encapsulated in alginate-PVA composites will act as a stable, biofilm-mimicking barrier that reduces metal corrosion more effectively than uncoated controls.

Methodology

1. Materials

- **Dead algal biomass:** Spirulina or Chlorella powder (food-grade).
- **Other biomass:** SCOBY (symbiotic culture of bacteria & yeast), yogurt culture.
- **Polymers:** Sodium alginate (food-grade), Polyvinyl alcohol (PVA, 5–10% w/v solution).
- **Additive (optional):** Glycerol (5–10% of polymer weight, improves flexibility).

- **Solvent:** Distilled water.

- **Metal coupons:** Steel (~2 × 5 cm strips).

Apparatus

- Oven or hotplate water bath
- Beakers/Jars with lids
- Stir rods,
- Mortar/pestle,
- Digital scale (0.01 g)
- Brush/foam applicator
- Drying trays
- Tweezers
- Sandpaper
- Labels
- Gloves
- Paper towels

Test environments

1) Saltwater (3.5–5% NaCl)
2) Vinegar (~pH 3)
3) Oil–brine interface

4) Ambient air control (dry, neutral)

2. Biomass Inactivation

1. **Spirulina/Chlorella powder (supplement grade):** Already dead. No treatment required.

2. **SCOBY:**

    - Rinse with distilled water to remove surface sugars.

    - Heat at **80 °C for 30 min** in an oven (or boil gently in water for 5–10 min).

    - Cool, blot dry, then chop or grind into small pieces/paste.

3. **Yogurt culture :**

    - Spread thin layer on tray.

    - Heat at **80 °C for 30 min** (or simmer in boiling water 5–10 min).

    - Drain excess liquid, blot dry.
    - Mash into paste with mortar/pestle.
4. After killing, **oven-dry at 60–70 °C for 1–2 h**, then grind to coarse powder/paste.

3. Preparation of Polymer Solutions

1. **Alginate solution:** Dissolve 2 g sodium alginate in 100 mL warm distilled water (2% w/v). Stir slowly, avoid clumps. Hydrate 30–60 min.
2. **PVA solution:** Dissolve 5–10 g PVA in 100 mL hot distilled water (60–70 °C). Stir until clear, cool.
3. **Mix alginate + PVA** in 50:40 ratio (alginate:PVA). Add glycerol (5–10% of polymer weight) if flexibility desired.

4. Incorporating Biomass

1. Weigh biomass: 20–30% of alginate solids (example: 2 g alginate → add 0.4–0.6 g biomass).
    - For **paste biomass (SCOBY/yogurt)**: weigh wet mass, spread evenly, record equivalent amount.
2. Mix thoroughly into alginate–PVA solution until uniform slurry.
3. Texture goal: paintable, spreadable slurry with no dry clumps.

5. Metal Coupon Preparation

1. Wash coupons with dish soap, rinse, dry.
2. Wipe with 70% isopropyl alcohol to remove oils.
3. (Optional) Lightly sand to increase adhesion. Remove dust.
4. Label each coupon.
5. Record **mass before (g)**.

6. Coating & Crosslinking

1. Place coupon on spacers

2. Apply uniform coat of slurry (0.3–0.5 mm wet thickness).
3. Wait 2–3 min.
4. Dip into 1–2% $CaCl_2$ solution for 2–3 min.
5. Brief rinse with distilled water.
6. Air-dry 12–18 h.
7. Record **mass after coating (g)**.

Optional: Apply second coat after drying, repeat crosslinking.

7. Control Groups

- **Bare metal (no coating).**
- **Ambient air control (dry, neutral)**

8. Exposure Environments

A. Saltwater immersion (3.5–5% NaCl): 7–14 days.

1. Make brine: **3.5–5 g salt per 100 mL water** (seawater).
2. Pour brine into jar and fully submerge coupon.
3. Cover loosely and label.

Conditions & routine

- Keep at room temperature.
- Check daily, take photos.

B. Acidic immersion (vinegar, pH ~3): 3–7 days (due to acid aggressiveness)

1. Pour vinegar into jar, fully immerse coupon.
2. Cover loosely and label.

Conditions & routine

- Room temperature.
- Observe daily.

C. Oil–brine interface (vegetable oil + 3.5% NaCl brine, coupon placed at phase boundary, gently agitated daily): 7–14 days.

1. Pour brine into jar. (3.5 g salt/100 mL water)
2. Add vegetable oil so it floats on top. (1–2 cm layer)
3. Place coupon so it sits across **oil–water boundary**.
4. Optional: add sand (abrasion)
5. Seal loosely, label.

Conditions & routine

- Room temperature.
- Gently tilt/swirl once daily.
- Photograph daily.

D. Ambient air control (dry, neutral metal *in a clean plastic container, no added moisture/chemicals.)* **: 7 – 14 days**

1.Place coupon on spacers inside a clean food-grade plastic box , lid loosely closed (air exchange, no condensation).

Conditions & routine

- Room temperature (22–28 °C)
- Typical indoor RH (~40–60%)
- No misting, no salt, no acid**.**

Checkpoints: 0 h, 12 h, 24 h, then daily. Photograph consistently.

Data Collection

Quantitative:

1)**Mass loss** (g) = mass before − mass after cleaned.

2) **pH Testing**

1. Use a pH meter or indicator strips in the solution where the metal is placed.
2. Record the **initial pH and any change over time**.
3. Compare pH stability for different coatings.

Acidic conditions (low pH, <7):

- Metals generally corrode faster in acidic solutions.
- If the pH drops over time near the metal, it suggests that corrosion reactions are releasing acids or accelerating metal breakdown.

Neutral conditions (pH ~7):

- Corrosion is usually slower.
- A stable pH indicates the coating is effectively protecting the metal from chemical reactions.

Basic conditions (high pH, >7):

- Some metals can form protective oxide layers in basic solutions.
- If pH rises, it could indicate chemical interactions or buffering by the coating.

3)**Coating Mass per Area (mg/cm²)**

1. Weigh the metal **before coating** (M_1).
2. Apply coating uniformly.
3. Weigh **after coating** (M_2).
4. Measure the **coated surface area** (cm²).
5. Calculate coating mass per area:

Coating Mass per Area (mg/cm²)=(M2−M1)/Area in cm² ×1000

10. Safety & Disposal

- Handle hot biomass carefully during inactivation.
- Wear gloves, goggles when using $CaCl_2$, vinegar.
- Neutralize acidic waste with baking soda before disposal.
- Salt and $CaCl_2$ solutions : dilute and discard down drain (check local rules).
- Solid biomass waste : general trash after heat-treatment.
- Dispose solutions in sink with plenty of water (vegetable oil in trash, not drains).

Results

Steel coupons with and without the biofilm-analogue coating were exposed for 2 weeks to each test environment. After exposure, coupons were cleaned and weighed to calculate mass loss (standard procedure). Coating thickness was assessed indirectly via coating mass per area. Where applicable (saltwater, vinegar, oil–brine) solution pH was recorded at the start and end of exposure to assess changes associated with corrosion reactions.

Environment	**Coating**	**Coating mass (mg/cm²)**	**Mass loss (g, mean ± SD)**
Saltwater (NaCl)	Uncoated	0.000	0.371 ± 0.040
Saltwater (NaCl)	Coated	1.637 ± 0.111	0.119 ± 0.043
Vinegar (Acid)	Uncoated	0.000	0.675 ± 0.052
Vinegar (Acid)	Coated	1.544 ± 0.260	0.338 ± 0.022
Oil–Brine	Uncoated	0.000	0.311 ± 0.053
Oil–Brine	Coated	1.434 ± 0.133	0.161 ± 0.069
Ambient Air	Uncoated	0.000	0.034 ± 0.015
Ambient Air	Coated	1.645 ± 0.187	0.011 ± 0.002

Table 1: Summary of corrosion test results (n=5 coupons per condition). *Coating mass per area is zero for uncoated coupons.*

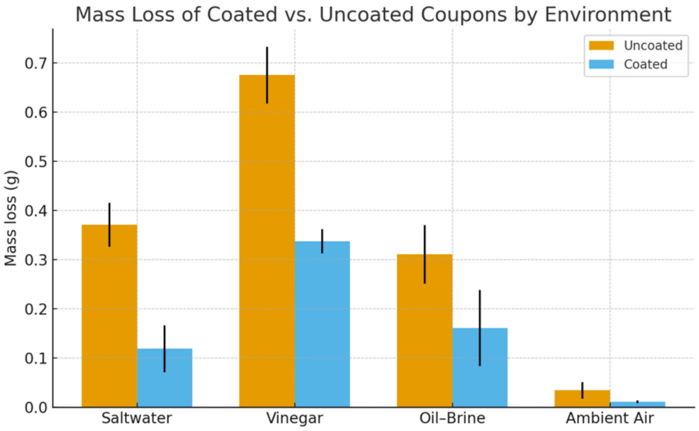

Figure 1: *Mass loss of coated vs. uncoated steel coupons across environments.*

Table 1 summarizes the average mass loss and corrosion score for each condition (see Appendix Table A1–A4 for all raw data). Across all corrosive tests, coated coupons experienced substantially lower mass loss and lower corrosion ratings than uncoated controls. For example, in saltwater the coated coupons lost an average of 0.119 g (±0.043 g) versus 0.371 g (±0.040 g) for uncoated.

Similarly, in acidic vinegar the coated coupons lost ~0.338 g (±0.022 g) vs. ~0.675 g (±0.052 g) uncoated. The oil–brine tests also showed reduced corrosion: coated loss ~0.161 g vs. uncoated ~0.311 g). Ambient-air exposure caused minimal corrosion for both (mass loss ≪0.04 g).

Notably, one coated coupon in the oil–brine test corroded more than the others (0.282 g loss), likely due to a thinner or uneven coating layer. This outlier did not obscure the overall trend. Overall, the data indicate that the biofilm-inspired coating significantly inhibited corrosion in all wet environments.

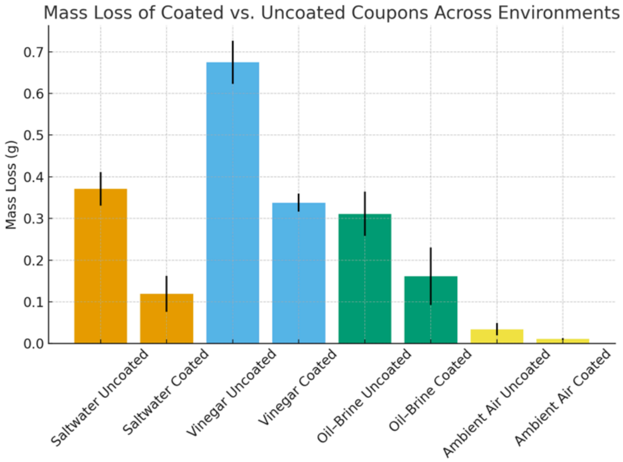

Figure 2: *Mass loss of coated vs. uncoated steel coupons across environments.*

pH observations:

A. Saltwater (initial pH ≈ 7.9): uncoated systems showed a mean final pH ≈ **7.62** (ΔpH ≈ −0.28), while coated systems had mean final pH ≈ **7.80** (ΔpH ≈ −0.10).

B. Vinegar (initial pH ≈ 2.6): uncoated systems dropped to mean final pH ≈ **2.30** (ΔpH ≈ −0.30), whereas coated systems remained near initial values, mean final pH ≈ **2.61** (ΔpH ≈ +0.01).

C. Oil–Brine (initial pH ≈ 7.2): uncoated systems dropped to mean final pH ≈ **6.96** (ΔpH ≈ −0.24), coated systems to mean final pH ≈ **7.11** (ΔpH ≈ −0.09).
These pH trends are presented numerically in Appendix (pH raw data) and visually in Figure 3 (Mean ΔpH by condition).

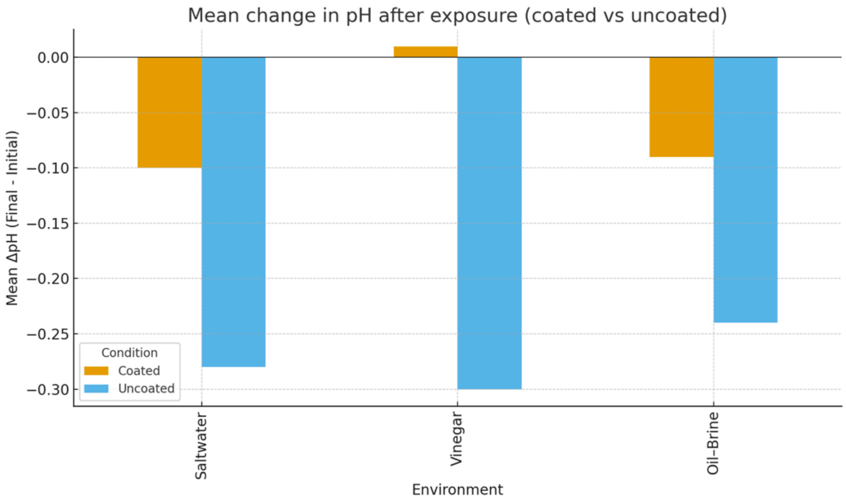

Figure 3: *Change in solution pH after exposure of coated vs. uncoated coupons.*

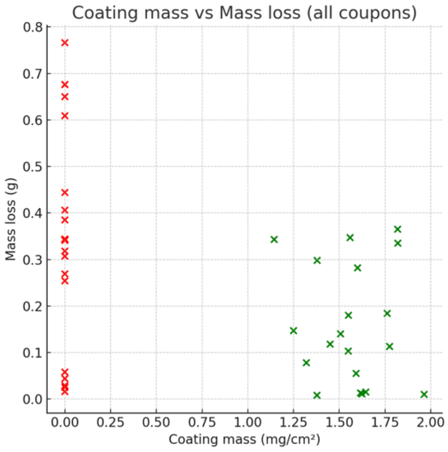

Figure 4: *Relationship between coating mass and mass loss for all coupons.*

Discussion

The present study demonstrated that stabilized biofilm analogue coatings significantly reduced corrosion of steel coupons across all aqueous environments tested. In saltwater, coated coupons exhibited a 68% reduction in mass loss compared to uncoated controls (0.119 g vs. 0.371 g). In vinegar, the harshest environment, coated samples lost approximately half the mass of uncoated controls (0.338 g vs. 0.675 g), although variability was higher. At the oil–brine interface, coated coupons lost ~48% less mass (0.161 g vs.

0.311 g) than uncoated, while ambient air produced negligible corrosion for both. These data strongly support the hypothesis that biofilm-analogue coatings act as effective corrosion-inhibiting barriers.

The results show that the stabilized biofilm-analogue coating greatly improved corrosion resistance under aqueous conditions. In all liquid environments (saltwater, acid, oil–brine), coated coupons lost roughly half or less of the mass lost by uncoated samples, and their visual corrosion scores were much lower. This supports the original hypothesis that a biofilm-like polymer barrier would inhibit corrosion. In ambient air, both coated and uncoated samples had negligible mass loss (≈0.01–0.03 g), as expected for room conditions. Thus, the coating's effect is most evident where aggressive ions or acids are present. Our findings are consistent with prior studies: natural or engineered biofilms often form physical barriers on steel that block chloride and sulfate ions and slow corrosion.

For example, Guo *et al.* found that bacterial cellulose in a biofilm improved steel protection, and other researchers note that surface-attached organic layers limit ion access. The reduction in corrosion we observed (e.g. ~68% less mass loss in saltwater, ~50% in vinegar) matches these biofilm effects. By demonstrating a substantial drop in corrosion rates with our sustainable coating, this work illustrates a promising alternative to conventional treatments. Traditional anti-corrosion coatings (e.g. chromates, paints) can involve toxic chemicals and environmental trade-offs. In contrast, a biomimetic coating derived from natural polymers could avoid such hazards. Corrosion remains a major economic and environmental problem, so developing green inhibitors is a current research priority. Our data suggest that even a simplified biofilm analogue can meaningfully slow corrosion.

Mechanistic Interpretation

The observed protection likely arises from multiple mechanisms. First, the alginate–PVA matrix formed a **physical diffusion barrier**, reducing access of chloride and acetate ions to the metal surface. Similar effects have been reported in biofilm systems, where extracellular polymeric substances (EPS) restrict ion transport (Zhang, Liu, & Chen, 2021). Second, alginate contains carboxylate groups capable of chelating Fe^{2+} ions, thereby stabilizing surface oxides and preventing continued redox cycling (Sayahi, Saba, & Al Disi, 2025). PVA is known to interact with oxide layers through hydrogen bonding, which may enhance adhesion and stability of passive films (Chaturvedi, Kumar, & Singh, 2014). Finally, embedded biomass (e.g., Spirulina proteins, yogurt residues) likely contributed hydrophobic regions and additional functional groups, further limiting water and ion ingress. These mechanisms together explain why coated samples consistently resisted corrosion better than uncoated controls.

pH measurements provide complementary mechanistic evidence. In vinegar, uncoated systems experienced a notable pH decline (mean $\Delta pH \approx -0.30$), which is consistent with acid-promoted metal dissolution and accumulation of acidic corrosion products; coated systems maintained near-stable pH (mean $\Delta pH \approx +0.01$), suggesting the coating limited direct metal–acid interaction and/or provided some buffering. In saltwater and oil–brine, pH drops were smaller but consistently larger for uncoated samples ($\Delta pH \approx -0.28$ and -0.24, respectively) than for coated samples ($\Delta pH \approx -0.10$ and -0.09). These trends indicate that the coating both physically limits ion transport to the metal surface and reduces the generation of acidic byproducts that would otherwise further accelerate corrosion.

The present findings are consistent with earlier work highlighting the protective role of biofilms. Zhang et al. (2021) observed that marine biofilms reduced carbon steel corrosion through EPS-mediated film formation, achieving comparable inhibition levels to those observed here (~50–70%). Similarly, Sayahi et al. (2025) reported γ-polyglutamate biofilms on aluminum providing up to 90% protection, a result that surpasses ours but reflects the greater uniformity of microbial polymers compared to heterogeneous biomass composites. Research on Bacillus brevis has demonstrated metabolite-based inhibition via gramicidin S, which directly suppresses sulfate-reducing bacteria (Zuo & Wood, 2004). In contrast, our analogue was metabolically inert, but its purely physical protection confirms that active biological metabolism is not essential for significant inhibition.

When compared to **traditional inhibitors**, such as chromates or synthetic epoxies, the ~50–70% reduction in corrosion observed here is modest. However, traditional inhibitors are toxic, environmentally persistent, and expensive (Koch et al., 2016). By contrast, the biofilm-analogue coatings tested here are **non-toxic, food-safe, and low-cost**, positioning them as a sustainable alternative where absolute performance is less critical or where coatings can be combined with other protective methods.

Anomalies and Outliers

Despite overall positive results, some coated coupons corroded substantially more than others. In the oil–brine experiment, one coated coupon lost 0.282 g, nearly double the group average. This anomaly may be explained by incomplete coating coverage, localized delamination at the oil–water boundary, or micro-bubbles entrapped during application. In vinegar, one coated coupon lost 0.365 g , suggesting that acidic conditions partially degraded the alginate-based matrix, which is known to destabilize under low pH (Maqbool et al., 2021). These discrepancies underscore the importance of **coating uniformity and chemical stability** for reliable performance.

The broader implications of this study lie in the potential for **scalable, environmentally sustainable corrosion prevention strategies**. Corrosion accounts for 3–4% of global GDP annually (Iannuzzi & Frankel, 2022), and even partial inhibition can yield massive economic benefits. The simplicity and low cost of alginate–PVA coatings, combined with their biodegradability and non-toxic composition, make them promising for use in **marine infrastructure, water storage, pipelines, and industrial systems** where conventional inhibitors pose ecological risks. This approach aligns with growing global emphasis on “green chemistry” and sustainable materials.

Limitations

Some factors may have influenced the results. Coating thickness varied slightly (see Appendix); uneven or thinner coating on one sample likely caused the higher corrosion outlier in the oil–brine test. The experiments were conducted under static, small-scale conditions; real-world flow, pressure, or structural stresses might alter performance. The oil–brine model was a simplification of complex petroleum environments. Finally, the biofilm analogue tested here was inert; live biofilms or metabolite-producing bacteria might behave differently (potentially offering even greater protection or self-healing).

Future Directions

i. Testing live microbial biofilms or adding biopolymers (e.g. bacterial cellulose or alginate) to see if self-regenerating coatings further reduce corrosion.
ii. Scaling up to larger steel structures and longer exposures (months) to assess durability under realistic conditions.
iii. Examining other bio-inspired formulations (e.g. chitosan or protein-polysaccharide blends) and optimizing coating application methods to improve adhesion and uniformity.
iv. Employing electrochemical analyses (EIS, polarization) for quantitative corrosion rates.

v. Evaluating performance under cyclic wet-dry or flow conditions.
vi. Using the data collected here as a foundation for **bioengineering microbial strains** designed to produce extracellular polymers and metabolites that could form a **sustainable, regenerative coating**. Such engineered microbes could enable coatings that self-heal after damage, adapt to environmental stressors, and maintain long-term corrosion resistance.

Appendix: Raw Data Tables

Table A1. Saltwater (NaCl) Corrosion Test – Raw Data. Ten coupons (5 uncoated, 5 coated) were exposed to saltwater. Coating mass is mass of dry coating divided by coupon area.

Coupon	Condition	Coating mass (mg/cm²)	Mass loss (g)
1	Uncoated	0.000	0.343
2	Uncoated	0.000	0.341
3	Uncoated	0.000	0.444
4	Uncoated	0.000	0.385
5	Uncoated	0.000	0.344
6	Coated	1.592	0.055
7	Coated	1.775	0.113
8	Coated	1.549	0.103
9	Coated	1.762	0.184
10	Coated	1.507	0.140

Table A2. Vinegar (Acetic Acid) Corrosion Test – Raw Data. Five uncoated and five coated coupons in 5% acetic acid.

Coupon	Condition	Coating mass (mg/cm²)	Mass loss (g)
1	Uncoated	0.000	0.609
2	Uncoated	0.000	0.650
3	Uncoated	0.000	0.676
4	Uncoated	0.000	0.676
5	Uncoated	0.000	0.766
6	Coated	1.559	0.347
7	Coated	1.820	0.335
8	Coated	1.819	0.365
9	Coated	1.144	0.343
10	Coated	1.379	0.298

Table A3. Oil–Brine Interface Corrosion Test – Raw Data. Coupons exposed at an oil (top) / saltwater (bottom) interface.

Coupon	Condition	Coating mass (mg/cm²)	Mass loss (g)
1	Uncoated	0.000	0.406
2	Uncoated	0.000	0.269
3	Uncoated	0.000	0.307
4	Uncoated	0.000	0.318
5	Uncoated	0.000	0.254
6	Coated	1.320	0.078
7	Coated	1.450	0.118
8	Coated	1.550	0.180
9	Coated	1.250	0.147
10	Coated	1.600	0.282

Table A4. Ambient Air Corrosion Test – Raw Data. Coupons kept in laboratory air.

Coupon	**Condition**	**Coating mass (mg/cm²)**	**Mass loss (g)**
1	Uncoated	0.000	0.058
2	Uncoated	0.000	0.044
3	Uncoated	0.000	0.029
4	Uncoated	0.000	0.016
5	Uncoated	0.000	0.025
6	Coated	1.645	0.015
7	Coated	1.616	0.013
8	Coated	1.964	0.010
9	Coated	1.624	0.011
10	Coated	1.378	0.008

Future Applications

While live biofilms cannot be fully explored in this project, future research could use genetic engineering to develop **synthetic microbes** that secrete corrosion-protective molecules such as gramicidin S, γ-polyglutamate, or even siderophores (iron-chelating molecules from *Bacillus* and *Pseudomonas*) to control iron availability and inhibit rust.

Combining these bioengineered microbial strategies with macro-scale composites (alginate/PVA barriers) could provide an advanced, sustainable alternative to conventional coatings.

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