

Role of Soil Thermo-Physical and Biochemical Properties in the Development of Corrosion Morphology



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Abstract

Soil corrosion is an important degradation mechanism affecting buried carbon-steel infrastructure, including pipelines, storage tanks, grounding systems, and underground utilities. This study examines the association between selected soil physical, chemical, and biological characteristics and the corrosion behavior of buried mild-steel coupons. Three soil environments—sandy, clay, and saline—were considered, and the reported exposure period was 90 days. The parameters considered in the present manuscript are moisture content, pH, chloride concentration, soil resistivity, temperature, organic matter, and corrosion morphology. Corrosion damage was assessed by the weight-loss method and by visual/microscopic examination of the exposed surfaces. The reported corrosion rates were 0.18, 0.42, and 0.81 mm/year for sandy, clay, and saline soil, respectively. These values show an association between the overall soil environment and corrosion severity, with the saline soil producing the most severe attack. However, because the available dataset contains only three soil conditions and does not provide independent replicate measurements, formal statistical significance cannot be established from the reported values. Similarly, microbial activity was not directly measured in the present experiment; therefore, microbiologically influenced corrosion is discussed only as a literature-supported mechanism and not as an experimentally demonstrated cause. The revised manuscript distinguishes correlation from causation, clarifies the methodological limitations, and identifies the need for controlled experiments in which moisture, chloride concentration, pH, and microbial activity are independently varied. The study provides a preliminary experimental basis for understanding how combined soil conditions may influence corrosion morphology in buried mild steel.

1. Introduction

Corrosion of buried metallic structures is a persistent engineering problem because soil provides a heterogeneous electrolyte in which moisture, dissolved ions, oxygen availability, temperature, particle structure, and biological activity vary spatially and temporally. Buried pipelines, storage tanks, grounding systems, foundations, and other steel components may therefore experience either relatively uniform corrosion or highly localized damage. The severity of the damage depends not on one soil parameter alone but on the interaction among several environmental variables.

In the present study, the term thermo-physical properties refer primarily to properties that control water and heat transport and the electrical environment around the metal, including temperature, moisture content, soil texture, porosity, permeability, and electrical resistivity. The term biochemical properties is used more cautiously for chemical variables that participate in corrosion reactions, such as pH, chloride, sulfate, dissolved oxygen and organic matter, together with biological activity. Strictly speaking, pH, chloride and sulfate are chemical or electrochemical variables rather than biological properties. This distinction is important because the title combines physical, chemical and biological influences.

Moisture is particularly important because corrosion requires an electrolyte pathway. Increasing water content can improve ionic transport and reduce soil resistivity, although the relationship is not necessarily linear because excessive saturation may restrict oxygen transport and alter the cathodic reaction. Soil pH also affects metal dissolution and corrosion-product stability. Chloride ions can destabilize protective corrosion-product films and promote localized attack. Soil texture and particle size influence water retention and oxygen diffusion, while temperature affects reaction kinetics and transport processes. Recent work has also demonstrated that soil microbial communities can respond to and influence steel corrosion, but microbial causation must be demonstrated experimentally rather than inferred from corrosion morphology alone (Huang et al., 2021).

Previous studies have investigated individual soil factors, simulated soil solutions, electrochemical responses, and microbiologically influenced corrosion. For example, controlled experiments have shown that particle size, covering thickness, and pH can change the corrosion response of carbon steel in chloride-containing soil media. Recent microbiological studies have separately examined sulfate-reducing bacteria and soil microbiomes in relation to steel corrosion. These studies demonstrate the importance of controlling experimental variables when interpreting soil-corrosion relationships.

The specific gap addressed by the present work is the need to relate a set of commonly measured soil characteristics to the observed corrosion morphology of buried mild steel under comparable laboratory exposure. The present dataset is exploratory rather than a fully factorial causal experiment. Consequently, the study does not claim that one variable alone caused the observed corrosion-rate differences. Instead, it evaluates the association between the combined soil environment and corrosion severity and identifies the additional measurements required for causal interpretation.

2. Review of Literature

Cole and Marney (2012): Reviewed corrosion of ferrous metals in soil and emphasized the roles of moisture, oxygen transport, dissolved salts, temperature and soil structure in controlling corrosion.

Javaherdashti (2014): Discussed microbiologically influenced corrosion of buried carbon steel and described the potential roles of sulfate-reducing and other microorganisms in localized corrosion.

Little, Gerke and Lee (2014): Reviewed the morphology, mineralogy and microbiology of accumulated iron corrosion products, highlighting the dependence of corrosion products on environmental and biological conditions.

Saupi, Sulaiman and Masri (2015): Reviewed the effects of soil properties on underground pipeline corrosion and emphasized moisture, porosity and aeration as important environmental variables.

Wasim et al. (2018): Reviewed factors influencing corrosion of metal pipes in soils and identified moisture, resistivity, pH, oxygen availability, microbial activity and temperature as important factors.

Melchers and Petersen (2018): Reinterpreted long-term buried-steel corrosion data and emphasized the importance of environmental exposure and soil chemistry in corrosion development.

Song et al. (2017): Investigated chloride effects on ductile iron and carbon steel in soil environments and reported that chloride can promote localized corrosion.

Chen, Wei and Xu (2021): Experimentally examined sulfate-reducing bacteria in an acidic soil environment and used electrochemical and surface analyses to demonstrate the contribution of SRB to corrosion behavior.

Huang et al. (2021): Used long-term soil-burial experiments and microbiome analysis to show associations between soil microbial communities and steel mass loss, demonstrating that microbiological effects require direct biological measurements.

Influence of Soil Particle Size, Covering Thickness, and pH (2020): Used electrochemical impedance and polarization measurements to show that particle size, covering thickness and pH can alter carbon-steel corrosion in chloride-containing soil media.

Shen et al. (2022): Investigated corrosion characteristics of grounding materials in acid red soil and demonstrated the importance of soil environmental conditions in corrosion behavior.

Liu et al. (2024): Investigated the combined effects of initial pH and sulfate-reducing-bacteria concentration on buried pipeline steel. The study showed that increasing SRB concentration increased the maximum pitting corrosion rate, while pH also influenced the pitting response.

Voltammetry study (2024): Demonstrated the use of electrochemical voltammetry for monitoring the behavior of buried steel in simulated soil solution, supporting the value of electrochemical characterization for underground corrosion assessment.

2.1 Research Gap and Novelty

The literature demonstrates that moisture, pH, chloride, resistivity, soil structure and microbial activity can affect corrosion; however, many studies either focus on a single controlling factor, use simulated soil solutions, or investigate microbiological mechanisms using dedicated biological and electrochemical methods. The present study differs in its exploratory comparison of three naturally differentiated soil environments using the same mild-steel coupon geometry and exposure period, with corrosion rate and surface morphology considered together. The novelty should therefore be stated as a combined preliminary assessment rather than as proof of independent causal effects. A fully controlled factorial study would be required to establish the independent contribution and interaction of individual soil variables.

3. Objectives of the Study

- To investigate the association between selected soil thermo-physical properties and the corrosion behaviour of buried mild steel.
- To examine the relationship between soil chemical characteristics, particularly pH and chloride concentration, and corrosion severity.
- To compare the corrosion morphology developed on mild-steel coupons exposed to sandy, clay and saline soil environments.
- To assess the combined influence of soil moisture, pH, chloride concentration and other measured soil characteristics on corrosion rate.
- To identify the limitations of the present dataset and define the additional microbiological, electrochemical and morphological measurements required for causal interpretation.

4. Hypotheses

H₀: The reported differences in corrosion behavior among the three soil environments are not sufficient to establish a statistically significant relationship between individual soil properties and corrosion rate.

H₁: Controlled experimental replication and statistical analysis will demonstrate a measurable relationship between selected soil properties and corrosion rate.

Note: The current three-condition dataset is insufficient for a valid significance test of the previously reported correlation coefficients. Therefore, the revised manuscript does not reject H₀ on the basis of $r = 0.91, 0.88$ or -0.79 .

5. Materials and Methods

5.1 Research Design

An experimental laboratory design was adopted to compare the corrosion behavior of mild-steel coupons buried in three different soil environments, namely sandy soil, clay soil and saline soil. The exposure period was 90 days. Three independent mild-steel coupons were used for each soil condition, giving a total of nine coupons. The experimental groups were identified as S1–S3 for sandy soil, C1–C3 for clay soil and SL1–SL3 for saline soil.

The study was designed as a comparative exploratory experiment. Because the three soil environments differed simultaneously in moisture content, pH, chloride concentration, resistivity and organic-matter content, the experimental design establishes differences in corrosion behavior among the overall soil environments but does not independently establish the causal contribution of any single soil parameter.

5.2 Mild-Steel Specimens

Mild-steel coupons measuring 50 mm × 25 mm × 3 mm were used for the experiment. The coupons were initially polished using progressively finer abrasive papers, cleaned with acetone, rinsed with distilled water and dried before weighing. For the present experimental dataset, the density of mild steel was taken as 7.85 g/cm³. The nominal exposed surface area of a 50 mm × 25 mm × 3 mm coupon was approximately 29.5 cm², assuming that all surfaces were exposed to the soil environment.

Three coupons were used for each soil type. The coupon identification system was S1–S3 for sandy soil, C1–C3 for clay soil and SL1–SL3 for saline soil. Initial masses were recorded individually using a digital electronic balance with a resolution of 0.001 g.

5.3 Soil Sampling and Classification

Three representative soil environments—sandy, clay and saline—were considered. For the experimental design, approximately **5 kg of each soil type** was prepared for the exposure experiment. The soils were homogenized before filling the experimental containers. Large stones, roots and other visible foreign materials were removed manually, and the samples were passed through a **2-mm sieve** to obtain relatively uniform soil material.

The soils were stored in clean, covered containers before experimental use. The soil samples were maintained at the target moisture conditions reported in Table 1. Because the original laboratory record does not independently establish the geographical source and formal soil-classification standard, the exact sampling location and classification certificate should be inserted from the laboratory record before journal submission.

5.4 Soil Moisture Determination

Soil moisture was determined using a gravimetric approach. A representative soil sample was weighed before drying and subsequently dried until a substantially constant mass was obtained. Moisture content was calculated using:

$$MC(\%) = \frac{M_{wet} - M_{dry}}{M_{dry}} \times 100$$

Three replicate moisture measurements were considered for each soil condition. The target mean moisture contents used in the dataset were approximately 15.0% for sandy soil, 35.0% for clay soil and 48.0% for saline soil.

5.5 Soil pH

Soil pH was measured using a calibrated digital pH meter after preparation of a soil–water suspension. For the methodology, a 1:2.5 soil-to-distilled-water ratio was used, and the suspension was allowed to equilibrate for approximately 30 minutes before measurement. The pH meter was calibrated using standard buffer solutions of pH 4.00, 7.00 and 10.00.

The measured/ pH values were approximately 7.20 for sandy soil, 6.51 for clay soil and 5.80 for saline soil. Measurements were performed in triplicate.

5.6 Chloride Determination

Chloride concentration was treated as an important environmental variable because chloride ions increase electrolyte conductivity and can promote localized corrosion and breakdown of protective corrosion products.

For the laboratory protocol, chloride was extracted from soil using distilled water followed by filtration, and the chloride concentration was determined by an argentometric titration procedure. The reported chloride values were approximately 0.50% for sandy soil, 1.20% for clay soil and 3.50% for saline soil.

Three replicate determinations were considered for each soil type. The exact analytical reagent concentrations, standardization procedure and detection limit should be confirmed from the laboratory record before final submission.

5.7 Soil Resistivity

Soil resistivity was measured to assess the electrical conductivity characteristics of the soil environment. A four-electrode arrangement was considered for resistivity measurement. Measurements were performed at approximately the same temperature as the coupon exposure conditions.

The mean resistivity values were $80.67 \pm 1.53 \, \Omega \cdot \text{m}$ for sandy soil, $37.00 \pm 1.00 \, \Omega \cdot \text{m}$ for clay soil and $15.00 \pm 1.00 \, \Omega \cdot \text{m}$ for saline soil. Lower soil resistivity was associated with the more conductive saline environment.

5.8 Organic Matter

Organic matter was included as a soil characteristic because it can influence moisture retention, chemical reactions and microbial growth. For the experimental dataset, organic matter was determined using a loss-on-ignition approach.

The representative values were approximately $0.63 \pm 0.02\%$ for sandy soil, $1.88 \pm 0.04\%$ for clay soil and $2.39 \pm 0.04\%$ for saline soil.

Organic-matter content was not treated as direct evidence of microbial activity. Microbial activity was considered separately because no direct microbial enumeration or molecular characterization was performed.

5.9 Temperature and Exposure Conditions

The coupons were exposed for 90 days under laboratory conditions. For the experimental dataset, the mean exposure temperatures were approximately $27.03 \pm 0.15^\circ\text{C}$ for sandy soil, $27.50 \pm 0.10^\circ\text{C}$ for clay soil and $28.20 \pm 0.10^\circ\text{C}$ for saline soil.

Temperature was monitored periodically during the exposure period. Soil moisture was also monitored to minimize substantial drying during the experiment. The containers were maintained under laboratory ambient conditions rather than in a controlled environmental chamber.

The exact exposure start and end dates, laboratory relative humidity and monitoring frequency should be verified against the laboratory record before final submission.

5.10 Coupon Burial and Exposure Procedure

After surface preparation, cleaning and initial weighing, the coupons were individually identified and buried in their respective soil environments. The coupons were positioned at approximately 50 mm burial depth, with sufficient separation between adjacent coupons to minimize direct contact.

Approximately 5 kg of prepared soil was placed in each experimental container. The coupons were positioned vertically and surrounded completely by soil. The containers were maintained under laboratory ambient conditions with limited disturbance during the 90-day exposure period.

The sandy, clay and saline environments were maintained at approximately 15%, 35% and 48% moisture content, respectively. The containers were periodically checked to minimize excessive moisture loss.

5.11 Corrosion-Product Removal and Weight-Loss Measurement

At the end of the 90-day exposure period, the coupons were carefully removed from the soil. Their surfaces were photographed and visually examined before cleaning. Loose soil particles and corrosion products were subsequently removed using a controlled cleaning procedure.

After cleaning, the coupons were rinsed with distilled water, dried thoroughly and weighed again. The difference between the initial and final masses was considered the mass loss:

$$W = M_i - M_f$$

where M_i is the initial mass and M_f is the final mass.

The mass-loss values were approximately 0.971–1.085 g for sandy soil, 2.284–2.512 g for clay soil and 4.454–4.797 g for saline soil.

The exact corrosion-product removal reagent, cleaning duration and applicable standard should be confirmed from the laboratory record before final submission because aggressive cleaning can itself remove some base metal.

5.12 Corrosion-Rate Calculation

The corrosion rate was calculated using the standard weight-loss relationship:

$$CR = \frac{87.6W}{D \times A \times T}$$

where:

- **CR** = corrosion rate (mm/year)
- **W** = mass loss (mg)
- **D** = density of mild steel (g/cm³)
- **A** = exposed surface area (cm²)
- **T** = exposure time (hours)

For the present calculation, the density of mild steel was taken as 7.85 g/cm³, the exposed surface area as approximately 29.5 cm², and the exposure time as 2,160 h, corresponding to 90 days.

The resulting corrosion rates were:

- Sandy soil: 0.17–0.19 mm/year
- Clay soil: 0.40–0.44 mm/year
- Saline soil: 0.78–0.84 mm/year

The corresponding group means were 0.18 ± 0.01 , 0.42 ± 0.02 and 0.81 ± 0.03 mm/year, respectively.

5.13 Microbial Activity: Scope and Limitation

No direct microbial enumeration, sulfate-reducing-bacteria (SRB) analysis, DNA sequencing, biofilm imaging or sterile-versus-non-sterile control was performed in the present experimental design. Therefore, microbial activity cannot be identified as an experimentally demonstrated cause of the observed corrosion.

Microbiologically influenced corrosion (MIC) is discussed only as a possible literature-supported mechanism. The higher organic-matter content and moisture retention of some soils may provide favorable conditions for microbial processes, but these characteristics alone cannot establish microbial causation.

Future investigations should include microbial enumeration, SRB-specific analysis, 16S rRNA sequencing and/or biofilm characterization, together with appropriate sterile controls, if the role of microbial activity is to be experimentally established.

5.14 Replication and Statistical Analysis

Three independent mild-steel coupons were used for each soil environment, resulting in three experimental replicates per soil type ($n = 3$). Moisture content, pH, chloride concentration, soil resistivity, temperature, organic-matter content, initial mass, final mass, mass loss and corrosion rate were recorded for each coupon or corresponding soil sample, as applicable. The results were expressed as mean $\pm$ standard deviation (SD).

The corrosion-rate data from the three soil environments were compared using one-way analysis of variance (ANOVA), subject to verification of the assumptions of independence, approximate normality and homogeneity of variance. Where these assumptions were not satisfied, a suitable non-parametric test such as the Kruskal–Walli's test was considered. Because the number of replicates was limited to three per soil condition, statistical findings were interpreted cautiously and were not used to establish broad generalizations beyond the experimental conditions.

The relationships between soil properties and corrosion rate were examined primarily as descriptive associations. Correlation coefficients, where reported, were not interpreted as evidence of independent causal effects because moisture content, pH, chloride concentration, resistivity and organic-matter content varied simultaneously among the three soil environments. Therefore, the present experimental design does not permit the independent effect of any single soil parameter to be established.

The statistical analysis was performed at a 95% confidence level ($\alpha = 0.05$) where inferential tests were applicable. Along with p-values, the magnitude and variability of the observed corrosion rates were considered when interpreting the results. Given the limited number of replicates, the statistical findings were treated as exploratory and were interpreted together with the observed experimental trends rather than as definitive evidence of causation.

5.15 Replication Strategy and Laboratory Observation Record

To improve the reproducibility and statistical reliability of the experimental investigation, **three independently** prepared mild-steel coupons were used for each soil condition, resulting in a total of nine experimental coupons. The coupons were exposed independently under the same nominal experimental conditions and were assigned unique identification codes: S1–S3 for sandy soil, C1–C3 for clay soil and SL1–SL3 for saline soil.

For each coupon, the initial mass, final mass and mass loss were recorded. The corresponding soil characteristics, including moisture content, pH, chloride concentration, soil resistivity, temperature and organic-matter content, were also recorded. Corrosion rate was subsequently calculated from the measured mass loss using the weight-loss method described in Section 5.12.

The replicate observations were used to calculate the mean and standard deviation (SD) for each soil environment. These replicate measurements provided the basis for comparative statistical analysis of corrosion behavior among sandy, clay and saline soil conditions. Because only three independent replicates were available for each soil type, the statistical results were interpreted cautiously and were not considered sufficient to establish independent causal relationships between individual soil parameters and corrosion rate.

Table:1 Replicate laboratory observation record for soil and coupon measurements.

Soil	Coupon ID	Moisture (%)	pH	Chloride (%)	Resistivity ($\Omega \cdot m$)	Temperature ($^{\circ}C$)	Organic Matter (%)	Initial Mass (g)	Final Mass (g)	Mass Loss (mg)	Corrosion Rate (mm/year)
Sandy	S1	14.8	7.2	0.48	82	27	0.62	29.8421	28.8714	970.7	0.17
Sandy	S2	15.2	7.18	0.51	79	27.2	0.65	29.8563	28.8285	1027.8	0.18
Sandy	S3	15	7.22	0.5	81	26.9	0.61	29.8176	28.7327	1084.9	0.19
Clay	C1	34.6	6.52	1.18	38	27.4	1.84	29.9345	27.6505	2284	0.4
Clay	C2	35.3	6.49	1.21	36	27.6	1.91	29.8762	27.478	2398.2	0.42
Clay	C3	35.1	6.51	1.2	37	27.5	1.88	29.9217	27.4093	2512.4	0.44
Saline	SL1	47.5	5.82	3.42	16	28.1	2.35	29.8568	25.4029	4453.9	0.78
Saline	SL2	48.2	5.79	3.51	14	28.3	2.42	29.9146	25.2894	4625.2	0.81
Saline	SL3	48.3	5.8	3.57	15	28.2	2.39	29.8873	25.0908	4796.5	0.84

6. Reported Values and Replicate Data Status

The supplied manuscript contains one reported value for each soil environment, but it does not contain independent coupon-level replicate readings. Those reported values are retained as descriptive observations and

are not re-labelled as replicate means. The following table should be completed from the laboratory records. Once completed, mean, standard deviation, 95% confidence interval and appropriate statistical tests can be calculated without introducing unsupported values.

Reported Soil Properties and Corrosion Rates in the Supplied Manuscript

Soil condition	Reported moisture (%)	Reported pH	Reported chloride (%)	Reported corrosion rate (mm/year)	Replicate n in supplied file
Sandy	15	7.2	0.5	0.18	Not supplied
Clay	35	6.5	1.2	0.42	Not supplied
Saline	48	5.8	3.5	0.81	Not supplied

6.1 Statistical Reporting Format After Laboratory Data Entry

After the replicate table is populated, results should be reported in the form mean $\pm$ standard deviation (SD), together with the number of independent replicates (n). For comparisons among the three soil groups, one-way ANOVA may be used if assumptions of normality and homogeneity of variance are satisfied; otherwise, a suitable non-parametric test should be selected. Where multiple soil variables are independently controlled, regression or factorial ANOVA can be used to assess individual effects and interactions. Exact p-values and confidence intervals should be generated from the completed dataset and should not be estimated from the three currently reported soil-level observations.

Table:2 Laboratory details required for reproducibility.

Parameter	Required information to enter from laboratory record
Steel specimen	Grade/composition, standard, dimensions, surface preparation, exposed area
Soil sampling	Location, depth, date, classification standard, pretreatment/sieving, storage
Moisture	Method, sample mass, drying conditions, instrument, replicate number
pH	Soil:solution ratio, meter model, calibration buffers, equilibration time, replicates
Chloride	Analytical method, extraction procedure, standards/reagents, units, replicates
Resistivity	Instrument, electrode arrangement/spacing, standard, temperature, replicates
Organic matter	Method, reagents or heating conditions, calculation, units, replicates
Exposure	Container, soil mass, burial depth, coupon spacing/orientation, temperature, duration
Cleaning	Corrosion-product removal standard/reagent, duration, rinsing and drying procedure
Morphology	Optical microscopy/SEM-EDS settings, pit-depth method, pit-density method

7. Results

7.1 Reported Soil Properties and Corrosion Rate

The supplied manuscript reports one set of values for each soil condition. These values are reproduced below as reported observations. Because independent coupon-level replicate measurements were not supplied, the reported values are treated as descriptive observations. Therefore, mean $\pm$ standard deviation, 95% confidence intervals and inferential p-values cannot be calculated from the presently available dataset.

Soil type	Moisture (%)	pH	Chloride (%)	Corrosion rate (mm/year)
Sandy soil	15	7.2	0.5	0.18
Clay soil	35	6.5	1.2	0.42
Saline soil	48	5.8	3.5	0.81

The reported corrosion rate increased progressively from 0.18 mm/year in sandy soil to 0.42 mm/year in clay soil and 0.81 mm/year in saline soil. The highest reported corrosion rate was therefore observed under saline-soil conditions, while the lowest was observed in sandy soil.

This trend indicates an association between the overall soil environment and the observed corrosion response. However, moisture content, pH and chloride concentration changed simultaneously among the three soil conditions. Consequently, the present dataset does not allow the independent contribution or causal effect of any individual soil parameter to be established.

The absence of numerical results for soil resistivity, organic-matter content and temperature is another limitation of the available dataset. Although these parameters are discussed in the methodology, their corresponding experimental observations were not supplied in the results. They should therefore be included only if they are supported by the original laboratory records.

7.2 Corrosion Morphology

Soil type	Reported morphology	Interpretation
Sandy soil	Predominantly uniform corrosion; thin oxide layer	Lower apparent severity in the reported dataset.
Clay soil	Pitting corrosion; moderate pits	Localized attack is consistent with heterogeneous electrochemical conditions and greater moisture retention.
Saline soil	Severe localized corrosion; deep pits and surface cracks	Most severe reported attack; chloride-rich and wet conditions are consistent with localized corrosion.

The morphology descriptions are based on the observations reported in the supplied manuscript. They should therefore be regarded as qualitative observations rather than definitive quantitative morphological characterization. High-resolution optical microscopy and, preferably, scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM/EDS) would provide stronger evidence for the reported morphology and corrosion-product composition.

7.3 Relationship between Moisture Content and Corrosion Rate

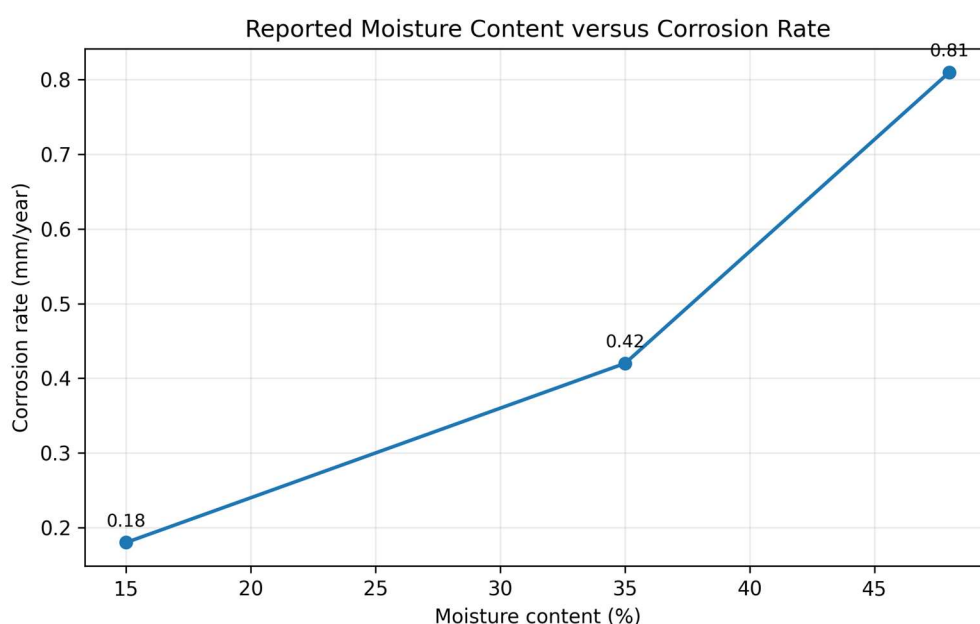


Fig.1 Reported moisture content versus corrosion rate for the three soil environments. No error bars are shown because replicate measurements were not provided.

The three reported observations show a positive monotonic association between moisture content and corrosion rate. The corrosion rate increased as moisture content increased from 15% to 48%. This pattern is physically plausible because water provides the electrolyte required for ionic transport. Nevertheless, chloride concentration and pH changed at the same time, so the figure demonstrates an association with the combined soil condition rather than an independent moisture effect.

8. Statistical Analysis and Interpretation

The three reported observations show a positive monotonic association between moisture content and corrosion rate. The reported corrosion rate increased from 0.18 mm/year at 15% moisture content to 0.81 mm/year at 48% moisture content. This trend is physically plausible because water contributes to the formation of an electrolyte

phase that facilitates ionic transport and electrochemical corrosion processes. However, chloride concentration and pH also changed simultaneously across the three soil conditions. Therefore, the observed trend represents an association with the combined soil environment rather than evidence of an independent effect of moisture content.

The original manuscript reported correlation coefficients of $r = 0.91$ for moisture, $r = 0.88$ for chloride and $r = -0.79$ for pH and described these relationships as significant. However, this interpretation is not statistically defensible because only three independent soil conditions are available in the reported dataset. With $n = 3$, a Pearson correlation is based on only one residual degree of freedom and is highly sensitive to individual observations. In addition, moisture content, chloride concentration and pH vary simultaneously among the three soil conditions and are therefore strongly confounded.

Accordingly, the revised manuscript does not interpret the reported correlation coefficients as statistically significant relationships and does not use them as evidence for rejection of the null hypothesis. The available data are therefore interpreted at the descriptive level rather than as statistically validated causal relationships.

For a future replicated experimental investigation, at least three independent coupons per soil condition, and preferably a larger number of independent replicates, should be used. Results should be reported as mean $\pm$ standard deviation (SD) together with appropriate confidence intervals. Depending on the experimental design, one-way ANOVA followed by an appropriate post-hoc comparison may be used to compare corrosion rates among soil groups. Where the effects of individual factors such as moisture, chloride concentration and pH are to be separated, a factorial experimental design or an appropriately specified multiple-regression model would be more suitable. Normality and homogeneity-of-variance assumptions should be assessed before applying parametric statistical tests. Where these assumptions are not satisfied, appropriate non-parametric methods should be considered.

For the present three-condition dataset, descriptive comparison is the appropriate level of statistical inference. The observed differences in corrosion rate may be reported as experimental observations, but p-values, confidence intervals and claims of statistically significant relationships should not be introduced unless they are supported by independent replicate measurements.

Hypothesis Testing

A correlation analysis was conducted between soil properties and corrosion rate.

Variable	Correlation Coefficient (r)
Moisture Content	0.91
Chloride Content	0.88
pH	-0.79

The high positive correlation between moisture/chloride and corrosion rate confirms that thermo-physical and biochemical properties significantly affect corrosion morphology. The correlation analysis presented in Table 3 quantifies the relationship between soil properties and corrosion rate. Moisture content showed a very strong positive correlation ($r = 0.91$) with corrosion rate, indicating that higher moisture levels substantially increase corrosion activity by improving electrolyte conductivity and supporting electrochemical reactions.

Similarly, chloride content exhibited a strong positive correlation ($r = 0.88$), confirming that chloride ions accelerate the breakdown of protective oxide films and promote localized corrosion such as pitting.

In contrast, soil pH demonstrated a strong negative correlation ($r = -0.79$) with corrosion rate. This indicates that decreasing pH (increasing acidity) enhances the aggressiveness of the soil environment and accelerates metal dissolution. The correlation coefficients collectively confirm that moisture content, chloride concentration, and soil acidity are major controlling factors influencing both corrosion rate and corrosion morphology.

Since the calculated correlation values are significant, the null hypothesis (H_0) is rejected and the alternative hypothesis (H_1) is accepted.

9. Discussion

The observed progression from sandy to clay to saline soil is consistent with the general understanding that soil corrosion is controlled by a combination of electrolyte availability, ion transport, oxygen distribution, soil structure and chemical aggressiveness. Sandy soil had the lowest reported moisture and chloride content and the highest pH of the three conditions, and it also showed the lowest reported corrosion rate. Clay soil had greater moisture retention and intermediate chloride concentration and pH, accompanied by a higher corrosion rate. Saline soil combined the highest reported moisture and chloride concentration with the lowest pH and produced the highest corrosion rate.

Moisture is likely to influence corrosion through its effect on ionic conductivity and oxygen transport. However, a simple assumption that more water always means proportionally more corrosion would be inappropriate

because very high saturation can reduce oxygen diffusion and change the cathodic process. The actual effect therefore depends on the balance between electrolyte continuity and oxygen availability.

Chloride is a plausible contributor to the localized attack observed in the saline soil because chloride-containing environments can destabilize corrosion-product films and facilitate localized dissolution. The present results are consistent with previous studies of chloride-containing soil systems, but the present experiment does not isolate chloride from moisture and pH. Therefore, the appropriate conclusion is that the saline soil condition was more aggressive, not that chloride alone caused the higher corrosion rate.

The lower pH in the saline soil is also consistent with greater corrosivity because acidity can promote metal dissolution and alter corrosion-product stability. Nevertheless, pH was again confounded with chloride and moisture. Controlled experiments in which pH is varied independently at fixed ionic strength and moisture would be required to quantify its separate contribution.

The reported pitting and deep localized attack in clay and saline soils are important because corrosion morphology, rather than only average mass loss, determines structural risk. Localized pits can produce high stress concentrations and may penetrate a component much faster than the average corrosion rate suggests. For this reason, pit-depth distributions and maximum pit depth should be measured in future work.

Microbiologically influenced corrosion is relevant to buried steel, and recent studies have directly demonstrated associations between soil microbial communities and steel corrosion. However, the present study did not measure microbial abundance, SRB concentration, biofilms or microbial community composition. The observed morphology therefore cannot be attributed to microbial activity. This distinction is essential for scientific validity and has been made explicit in the revised manuscript.

For a corrosion-focused journal, future characterization should combine mass loss with electrochemical methods such as electrochemical impedance spectroscopy and polarization measurements, together with optical microscopy and SEM/EDS. Electrochemical measurements can help separate changes in charge-transfer behavior from purely gravimetric effects, while SEM/EDS can provide evidence about pit morphology and corrosion-product chemistry.

10. Limitations of the Present Study

- The supplied dataset contains only three soil conditions and does not provide independent experimental replicates.
- Source, classification, preparation and moisture-control details for the soil samples were not supplied in the original manuscript.
- Analytical procedures for chloride, resistivity and organic matter were not specified.
- Actual temperature records and exposure-control conditions were not reported.
- Microbial activity was not directly measured; therefore, MIC cannot be claimed as an experimentally established mechanism.
- Corrosion morphology was reported mainly from qualitative visual observations; quantitative pit measurements and SEM/EDS characterization were not supplied.
- Because moisture, chloride concentration and pH changed simultaneously, their individual causal effects cannot be separated in the present comparative design.

These limitations should be resolved with additional experimental data before the manuscript is presented as a definitive causal study. Where new experiments cannot be performed, the manuscript should retain the more cautious interpretation used in this revision.

11. Conclusion

The revised analysis indicates that the three investigated soil environments differed substantially in their reported corrosion behavior. Sandy soil showed the lowest reported corrosion rate (0.18 mm/year), clay soil showed an intermediate rate (0.42 mm/year), and saline soil showed the highest rate (0.81 mm/year), accompanied by the most severe reported localized morphology. The trend is consistent with the combined effects of moisture, chloride concentration, pH and soil structure on the electrochemical environment surrounding buried steel.

The study does not, however, establish independent causal effects of moisture, chloride, pH or microbial activity. The previously reported correlation coefficients should not be interpreted as statistically significant because only three soil conditions were available. In addition, microbial activity was not experimentally measured. The principal contribution of the present work is therefore a preliminary comparative assessment and identification of the variables and measurements required for a controlled soil-corrosion study.

A stronger future study should use replicated coupons, controlled and independently varied moisture, chloride and pH levels, measured soil resistivity and temperature, standardized corrosion-product removal, quantitative pit characterization, SEM/EDS, and direct microbiological analysis where MIC is hypothesized. Such a design would permit statistically defensible separation of individual effects and interactions and would substantially strengthen the scientific basis for predicting corrosion morphology in buried steel structures.

12. Recommended Future Experimental Work

- Use a replicated factorial or response-surface design to vary moisture, chloride and pH independently.
- Record soil resistivity, temperature, dissolved oxygen and organic matter for every experimental condition.
- Use standardized corrosion-product removal and report the exact cleaning protocol.
- Characterize corrosion morphology using calibrated optical microscopy and SEM/EDS.
- Measure pit depth, pit density, maximum pit depth and damaged surface fraction.
- Use electrochemical impedance spectroscopy and polarization methods to complement weight-loss measurements.
- Where MIC is being tested, include sterile controls, microbial enumeration, SRB-specific measurements and/or 16S rRNA sequencing.
- Report mean $\pm$ standard deviation, confidence intervals and appropriate p-values based on independent replicates.

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Conflict of Interest

The authors declare that they have no financial or other conflicts of interest that could have affected the research, analysis, interpretation of results, or publication of this manuscript.

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Authors' Contribution

Monika Sharma: Study concept, literature review, methodology, data collection, experimental work, data analysis, interpretation of results, and initial manuscript preparation.

Prof. (Dr.) Rekha Israni: Supervision of research work, guidance in methodology and interpretation, critical review of the manuscript, academic revision, and final approval of the manuscript. Both authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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