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(Review Article)

Research progress on the corrosion of tin-bronze artifacts in red soil environments

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Abstract

Tin-bronze artifacts serve as invaluable historical carriers but face severe preservation challenges in red soil environments, which are widespread in southern China. Characterized by strong acidity, high active iron-aluminum oxide content, and complex aeration properties, red soils impose unique electrochemical corrosion dynamics distinct from neutral environments. This review summarizes the fundamental corrosion mechanisms of tin-bronze, elaborating on the specific impacts of key red soil physicochemical properties—such as pH, redox potential, and microbial activity—on corrosion behavior. It explores the macroscopic and microscopic characteristics of corrosion phenomena while analyzing the complex interplay of soil, alloy, and environmental factors influencing corrosion rates. Furthermore, the paper addresses current research limitations and outlines critical future directions, including micro-interface reaction mechanisms, long-term kinetics modeling, and differential studies on red soil subtypes. Ultimately, this work aims to provide comprehensive theoretical support and practical guidance for the scientific conservation of bronze artifacts excavated from red soil regions.

Keywords: Tin-Bronze; Bronze Artifacts; Soil Corrosion; Red Soil; Corrosion Mechanism; Corrosion Products

1. Introduction

Bronze, primarily an alloy of copper and tin, has played a vital role in human history due to its excellent casting properties, suitable hardness and strength, and unique color [1],This gave rise to a "Bronze Age" as glorious as that of the Shang and Zhou dynasties in China[2] .These ancient bronzes, including ritual vessels, weapons, tools, and ornaments, are not only material carriers of the social, political, economic, cultural, and belief systems of the time[3], but also direct evidence for studying ancient metallurgical casting technology, artistic styles, and social changes[4]. However, these precious heritages buried underground, after hundreds or even thousands of years, are all inevitably eroded by the surrounding environment, undergoing varying degrees of corrosion [5], leading to information loss and even structural damage [6].

Soil is the most common burial environment for bronze artifacts. Soil itself is an extremely complex system, and its physical, chemical and biological properties (such as pH value, water content, redox potential, ionic composition, microbial activity, texture and structure) together constitute a complex medium that affects metal corrosion [7]. Among the many soil types, red soil (Ferrallisols/Acrinols/Ulti sols, etc., according to different classification systems) has a special and significant impact on the bronze artifacts buried in it because it is widely distributed in tropical and subtropical humid areas (including large areas of southern China) [8] and has unique geochemical characteristics [9]. Many important archaeological discoveries, such as the Shang Dynasty tomb at Dengzhou in Xingang, Jiangxi [10] the Tong Lushan Ancient Mining and Metallurgical Site in Daye, Hubei [11], and others are all located in typical red soil areas. Studies of bronze artifacts unearthed at these sites show that their corrosion often exhibits characteristics different from those in neutral or calcareous soil environments [12].

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Red soil is typically strongly acidic (pH 4.0-5.5), rich in highly reactive iron and aluminum oxides and hydroxides, with low organic matter content, high clay content [9], and complex physical structure and water-air conditions [13]. These characteristics directly relate to the electrochemical driving force, reaction pathway, product stability, and corrosion morphology of bronze corrosion. Therefore, a deep understanding of the corrosion behavior and mechanisms of tin bronze in this unique soil environment is not only an important issue for archaeology and cultural relic conservation, but also of crucial theoretical and practical significance for accurately assessing the value and preservation status of cultural relics, revealing information about ancient environmental changes [14], and formulating effective and targeted conservation and restoration strategies [15]. Building upon previous work, this paper will further review the research progress on the corrosion of tin bronze in red soil environments, explore the complex influence of key red soil characteristics on the corrosion process, analyze the corrosion products and morphological features, analyze the corrosion kinetics under the coupling effect of multiple factors, and propose more specific suggestions for future research directions.

2. Basic processes and products of soil corrosion of tin bronze

The corrosion of tin bronze in soil is essentially an electrochemical process**Error! Reference source not found.**, the rate of which and the products are controlled by both alloy composition and environmental conditions**Error! Reference source not found.**. The process involves a metal/alloy losing electrons and being oxidized and dissolved as an anode, and an oxidant in the environment (mainly oxygen) accepting electrons and being reduced as a cathode.

2.1. Electrochemical reaction

Anodic reaction: Metal atoms lose electrons, transforming into ions that enter the soil solution or form solid products. Copper and tin are the main reactants, and other elements in the alloy, such as lead and zinc, also participate.

- $Cu \rightarrow Cu^+ + e^-$ (usually occurs under low oxygen or complexing conditions)
- $Cu \rightarrow Cu^{2+} + 2e^-$ (more common in oxidizing environments)
- $Sn \rightarrow Sn^{2+} + 2e^- \rightarrow Sn^{4+} + 2e^-$ (Tin usually eventually oxidizes to +4 oxidation state)
- $Pb \rightarrow Pb^{2+} + 2e^-$

Cathode reaction: Depends on soil pH and oxygen content.

In well-aerated, near-neutral soils: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$

In well-aerated, acidic red soils: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ (This reaction proceeds more readily due to the high concentration of H^+)

Under anaerobic conditions (such as deep soils or saturated water): $2H^+ + 2e^- \rightarrow H_2$ (This reaction is significant only in strongly acidic conditions and when the potential is sufficiently negative) or other oxidized substances (such as Fe^{3+}) are reduced.

2.2. Corrosion product types and layered structures

The metal ions produced by anodic dissolution undergo a series of chemical reactions with water, dissolved CO_2, O_2, and anions such as Cl^-, SO_4^{2-}, and PO_4^{3-} in the soil solution**Error! Reference source not found.**, forming various corrosion products that typically coat the alloy surface**Error! Reference source not found.**. These products are not homogeneous mixtures, but often exhibit a distinct layered structure**Error! Reference source not found.**, reflecting the sequence of corrosion and differences in the microenvironment**Error! Reference source not found.**.

Common corrosion products and their formation conditions are as follows

2.2.1. Oxides/Hydrogenates

Cuprite (Cu_2O): Red or reddish-brown, usually the first corrosion layer forming immediately adjacent to the metal matrix. Relatively dense**Error! Reference source not found.**, it provides some protection. Forms under low-oxygen or weakly oxidizing conditions**Error! Reference source not found.**.

Tenorite (CuO): Black in color, it is an oxide of Cu (II), formed under stronger oxidizing conditions from Cu_2O or directly.

Cassiterite (SnO_2): White, gray, or yellow in color, it is the main corrosion product of tin, chemically very stable, and often accumulates in corrosion layers. It is sometimes considered beneficial for slowing corrosion**Error! Reference source not found.**.

2.2.2. Carbonates

Malachite ($Cu_2(OH)_2CO_3$): Green in color, it is one of the most common copper rusts and usually forms in neutral to slightly alkaline environments with CO_2 and moisture. It is not easily formed or is unstable in typical acidic red soils.

Azurite ($Cu_3(OH)_2(CO_3)_2$): Deep blue in color, it forms under similar conditions to malachite, but requires a higher CO_2 partial pressure**Error! Reference source not found.**.

Chloride: Atacamite ($Cu_2(OH)_3Cl$): Bright green or powdery, it is the infamous culprit behind "bronze disease," and its formation requires the participation of Cl^- ions. Cl^- can destroy the protective film of Cu_2O, forming a soluble CuCl intermediate. This intermediate then undergoes hydrolysis and oxidation to generate atacamite**Error! Reference source not found.**, releasing Cl^- which continues to participate in the reaction, leading to a cyclical breakdown**Error! Reference source not found.**. It is more likely to occur when the relative humidity is above ~35%.

Sulfate: Brochantite ($Cu_4(OH)_6SO_4$): Green in color, formed in environments containing sulfate ions (possibly from acid rain, oxidation of sulfur-containing minerals, or agricultural pollution)**Error! Reference source not found.**.

Phosphate: Libethenite ($Cu_2(PO_4)(OH)$): Can form in phosphate-rich soils (such as those from bone decomposition in burial sites), and is dark green in color**Error! Reference source not found.**.

Table 1 A brief description of common corrosion products of tin bronze and their formation environment

Corrosion product name (chemical formula)	**Colors**	**Main formation environment/conditions**	**Notes/Hazards**
Cuprite (Cu_2O)	Red/Reddish Brown	Located close to the substrate, in a weak oxidation/reduction environment, it is often used as an inner layer.	It may have some protective effect.
Calpene (CuO)	Black	Strong oxidizing environment	-
Castanol (SnO_2)	White/Gray/Yellow	Stable oxidation products of tin often accumulate in the etched layer.	May slow down corrosion
Malachite ($Cu_2(OH)_2CO_3$)	Green	Neutral to weakly alkaline pH, containing H_2O, O_2, CO_2	Green copper rust is common, but rare/unstable in acidic red soils.
Azurite ($Cu_3(OH)_2(CO_3)_2$)	Dark Blue	Similar to malachite, but requires a higher CO_2 concentration.	-
Copper chloride ($Cu_2(OH)_3Cl$) (Multiple allotropes)	Bright Green/Powder	The presence of Cl^- ions and humidity levels above 35% make it highly destructive.	The root cause of "bronze disease" is cyclic corrosion.

2.3. Stabilized rust (patina) and active corrosion

The term "verdigris" or "patina" usually refers to a relatively stable and dense layer of corrosion products that forms after long-term exposure to the atmosphere or burial environment. Sometimes it has aesthetic value and can provide some protection to the substrate [5]. However, under certain conditions, especially in the presence of high concentrations of Cl^- accompanied by humidity changes, the corrosion process remains active, generating loose, hygroscopic, and harmful rust that continuously erodes the substrate. This is known as "active corrosion" or "bronze disease"[23].

3. Characteristics of red soil environment and its detailed influence mechanism on tin bronze corrosion

The unique properties of red soil determine its special influence on the corrosion behavior of tin bronze, which differs significantly from corrosion in neutral or alkaline soils (such as calcareous soils).

3.1. Acidic environment (low pH)

The pH value of red soil is typically between 4.0 and 5.5, falling into the strongly acidic range. The effect of low pH on corrosion is manifested in: Increased cathodic reaction rate: As mentioned earlier, the oxygen reduction reaction ($O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$) has a stronger driving force under acidic conditions because of the higher concentration of the reactant H^+ [7].

Damage/Dissolution of Protective Product Layers: Many copper corrosion products are unstable under acidic conditions. For example, the inner Cu_2O layer, which is considered to have a certain protective effect, undergoes an acid dissolution reaction: $Cu_2O + 2H^+ \rightarrow 2Cu^+ + H_2O$ [26]. Common green carbonate rust layers (malachite, azurite) also dissolve at pH levels below approximately 5.5–6[22]. This makes it difficult for alloy surfaces to form a stable and effective protective film, leaving them continuously exposed to corrosive media.

Affecting Selective Dissolution of Elements: In acidic media, copper is generally more soluble than tin (standard electrode potentials $E^0(Cu^{2+}/Cu) = +0.34V$, $E^0(Sn^{2+}/Sn) = -0.14V$), which may lead to a relative enrichment of tin in the corrosion layer (forming SnO_2), the so-called "destannification," altering the composition and structure of the corrosion layer[27].

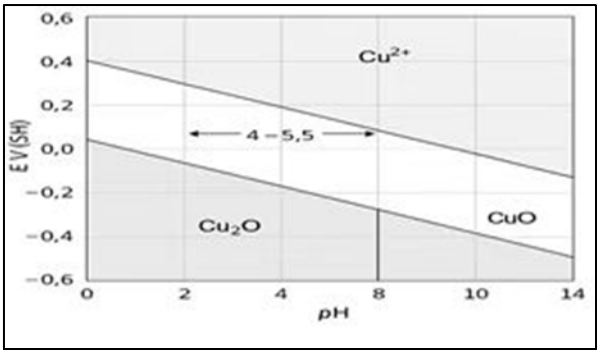

Figure 1 Simplified Pourbaix diagram of a copper-water system (pH effect)

3.2. High content of active iron and aluminum oxides

Red soil is rich in hydrated iron oxides (goethite, hematite, etc.) and alumina (gibbsite, etc.) colloids, with a content of up to 10% or more [9]. These components have:

Strong adsorption capacity: Their large specific surface area and surface charge characteristics enable them to strongly adsorb ions in the soil solution. In particular, they have a strong adsorption effect on anions such as Cl^-, SO_4^{2-}, and PO_4^{3-} [28], which may enrich these corrosive or passivating ions at the bronze-soil interface, change the chemical properties of the local microenvironment, and induce or aggravate local corrosion [29].

Affecting redox potential (Eh): Iron oxides (Fe^{3+}/Fe^{2+} system) themselves participate in the redox balance of the soil, which may affect the potential of the bronze surface, and even cause galvanic corrosion with bronze under certain conditions [30]. Physical covering and cementation: These fine particles are easy to fill the pores of corrosion products or cement together with corrosion products to form a hard "mixed layer of soil and rust". On the one hand, this may hinder the transmission of corrosive media, and on the other hand, it also brings difficulties to the cleaning and protection of cultural relics [11].

3.3. Soil texture, structure and water vapor conditions

Red soils typically have a high clay content (>30-40%) and a heavy texture, but their structure (such as the degree of aggregate formation) varies depending on the soil formation process and subsequent utilization history[9].

Water retention and conductivity: High clay content implies good water retention capacity. Moisture is an essential medium for electrochemical corrosion and a carrier for ion migration. Soil moisture content directly affects its resistivity; higher moisture content generally results in lower resistivity (better ionic conductivity), which is conducive to the formation of macroscopic corrosion cells and the conduction of corrosion current [31] .

Permeability and differentially charged cells: Heavy texture often leads to poor permeability, especially under compacted or water-saturated conditions. However, soils are not homogeneous and contain pores, fissures, and aggregate structures, resulting in uneven oxygen distribution. This difference in oxygen concentration forms a "differentially charged cell": areas with low oxygen concentration (such as parts in close contact with objects or deep cracks) become the anode, accelerating dissolution; while areas with sufficient oxygen supply (such as surfaces exposed to larger pores) become the cathode [16]. This is an important mechanism leading to localized corrosion such as pitting and crevice corrosion.

Wet-dry alternation effect: Seasonal rainfall or groundwater level changes in red soil areas can cause the burial environment to experience wet-dry alternation. This cyclical process is more destructive than continuous wet or dry conditions: corrosion occurs when wet, and salts concentrate locally when dry, which may crystallize and generate physical stress that destroys the corrosion layer; at the same time, oxygen can more easily enter the pores in the semi-dry state, accelerating the cathodic reaction in the subsequent wet period [32].

Figure 2 Schematic diagram of red soil profile and bronze burial environment

3.4. Ionic composition of soil solution

In addition to high concentrations of H^+, red soil solutions contain several other ions that significantly influence corrosion

Chloride ions (Cl^-): Cl^- is one of the most destructive ions in copper alloys. Its small radius and strong penetrability allow it to preferentially adsorb onto metal surfaces, damaging passivation films (especially Cu_2O layers), forming soluble monovalent copper chloride complexes (such as $CuCl_2^-$), preventing surface repassivation, and promoting anodic dissolution [24]. Even when the background Cl^- concentration in red soil is not high [28], the adsorption and enrichment effect of iron and aluminum oxides [29] or external pollution (such as proximity to the coast, saltworks sites, or human activities) can lead to an interfacial Cl^- concentration sufficient to cause severe corrosion (especially bronze disease).

Sulfate ions (SO_4^{2-}): Primarily derived from atmospheric deposition (acid rain), weathering and oxidation of sulfur-containing minerals (such as pyrite), or fertilizer application. SO_4^{2-} itself is less corrosive to copper than Cl^-, but under acidic conditions, its presence may participate in the formation of sulfate corrosion products (such as chalcanthite) and may synergistically accelerate corrosion [25]. Other ions: Phosphate (PO_4^{3-}) may form stable copper phosphate minerals under certain conditions (such as in burial sites) [5]. Organic acids in the soil (such as oxalic acid and citric acid, although organic matter in red soil is usually low, they may be present in some areas) may also complex with copper ions, affecting their dissolution and migration [33].

3.5. Microbial activity (MIC)

Soil is a kingdom of microorganisms. Although red soil is acidic [34], there are still microbial communities adapted to this environment. Microorganisms influence metal corrosion in various ways, namely microbiologically influenced corrosion (MIC) [35]: Metabolic product effects: Acid-producing microorganisms: For example, Thiobacillus can oxidize sulfides to produce sulfuric acid, further lowering the local pH and exacerbating acid corrosion. Sulfate-reducing bacteria (SRB): For example, Desulfovibrio reduces SO_4^{2-} to produce H_2S under anaerobic conditions. H_2S is highly corrosive to copper and can generate copper sulfide (CuS, Cu_2S) products [36]. SRB activity may exist in the deep layers of red soil or in micro-anaerobic environments. Organic acids: Microbial metabolism can produce a variety of organic acids, which can complex metal ions and promote dissolution. Biofilm formation: Microorganisms form biofilms on the surface of objects, creating microenvironments with uneven physical/chemical properties.

3.6. Biofilms may

- form differentially charged batteries (different oxygen concentrations inside and outside the membrane).
- accumulate corrosive ions or nutrients.
- prevent corrosion inhibitors from reaching the metal surface.
- directly participate in electron transfer processes.

Iron/manganese redox bacteria: Iron bacteria commonly found in red soil may participate in the Fe^{2+}/Fe^{3+} cycle, affecting the local redox potential [35].

Table 2 Main microbial groups in soil and their potential role in bronze corrosion

Microbial groups	**Metabolic characteristics/products**	**Potential impact on bronze corrosion**
Thiobacillus	Oxidation of sulfides to produce sulfuric acid (H_2SO_4)	Strong acidification exacerbates acid corrosion.
Sulfate-reducing bacteria (SRB)	Anaerobic, reducing SO_4^{2-} to produce H_2S	H_2S directly corrodes copper to form sulfides; cathodic depolarization.
Iron bacteria	Oxidizing Fe^{2+} or reducing Fe^{3+}	Affects local redox potential; forms iron oxide precipitates.
Organic acid producing bacteria	Metabolism produces oxalic acid, citric acid, acetic acid, etc.	Complexed copper ions promote dissolution; localized acidification
Microbial communities that form biofilms	Secretion of extracellular polymeric substances (EPS) to form biofilms	Differential inflation; ion enrichment; physical isolation; alteration of interfacial chemistry
Microbial groups	Metabolic characteristics/products	Potential impact on bronze corrosion

4. Corrosion Cases and Characteristic Analysis of Tin Bronze Artifacts Unearthed from Red Soil

Although there is a lack of extensive systematic comparative studies specifically on the corrosion of bronze artifacts in red soil environments, some typical corrosion characteristics that distinguish them from neutral/alkaline soil environments can be summarized from published analytical reports and empirical observations of bronze artifacts unearthed in several red soil regions (such as southern China[12], Southeast Asia, etc.): A general lack of typical green "malachite rust": Due to the acidity of red soil, malachite ($Cu_2(OH)_2CO_3$), which is stable in neutral to weakly alkaline environments, is difficult to form or preserve. The surface of artifacts often exhibits a red or reddish-brown hue dominated by cuprite (Cu_2O), or a dark brown or yellowish-brown rust layer formed by mixing with soil [21].

Relative enrichment of tin in the corrosion layer: The selective dissolution of copper under acidic conditions leads to a relative enrichment of more corrosion-resistant tin oxide (SnO_2) in the corrosion layer, sometimes even forming an almost pure SnO_2 shell or distributed between crystals [27]. This phenomenon is particularly evident in the study of ancient high-tin bronzes (such as bronze mirrors).

Pit corrosion, pitting corrosion, and perforation are common: The corrosive effect of Cl^-, differential galvanic cells, and microscopic inhomogeneities within the alloy (such as inclusions and segregation) more readily induce localized corrosion in acidic media, forming deep pits or even perforations [24]. The adsorption of Cl^- by iron and aluminum oxides in lateritic soil may exacerbate localized corrosion at the interface.

“Mineralization” or “soil-rust combination” phenomenon: Clay particles and iron-aluminum colloids in lateritic soil readily combine with corrosion products, forming a hard, dense, and difficult-to-remove soil-rust mixture layer, appearing as if the artifact itself has been “mineralized” [33]. This poses challenges for subsequent analysis and conservation treatment.

Loss of surface details and etched textures: Acidic corrosion usually leads to uniform dissolution of the surface metal or preferential dissolution along grain boundaries and phase boundaries, making fine patterns and inscriptions on the artifact surface easily blurred, presenting an etched appearance.

5. Factors affecting the corrosion rate of tin bronze in red soil

The corrosion rate of tin bronze in red soil is the result of a complex coupling of multiple factors, making it difficult to determine using a single factor. The main influencing factors can be summarized into the following categories:

5.1. Soil environmental factors

pH: A key factor. Lower pH generally indicates a greater tendency to corrode and a faster corrosion rate [26].

Moisture content and saturation: There exists a "critical moisture content" range where corrosion rates are fastest (typically when soil pores are partially filled with water and partially with air), providing sufficient electrolyte solution conductivity and adequate oxygen supply to support the cathodic reaction [31]. Rates may be lower when completely dry or completely water-saturated.

Oxygen concentration and gradient: Directly affects the cathodic reaction rate. Oxygen concentration gradients are a major cause of differentially charged cells, leading to localized corrosion [16].

Soil resistivity: Reflects the soil's conductivity. Low resistivity (usually due to high moisture content and high soluble salt content) facilitates corrosion current flow and promotes macroscopic corrosion cell activity [7]. Red soils have strong leaching and low soluble base ion content, potentially resulting in higher resistivity, but their high water-holding capacity and adsorbed ions reduce interfacial resistivity. Corrosive ion concentrations (Cl^-, SO_4^{2-}, etc.): Even low concentrations of Cl^- (tens of ppm) can significantly accelerate corrosion, especially under acidic conditions where it is easier to break through the passivation film [24]. The effect of SO_4^{2-} is relatively small, but it also contributes under certain conditions [25].

Microbial activity (MIC): The presence and activity of specific microorganisms can significantly alter the local microenvironment, increasing the corrosion rate by several orders of magnitude through acid production, sulfide production, and biofilm formation [36]. The mechanisms of action of acidophilic microorganisms in red soil environments are particularly noteworthy.

Oxidation-reduction potential (Eh): Reflects the strength of soil oxidation or reduction, affecting element valence states and reaction directions. The surface layer of red soil is usually highly oxidizing, while deeper layers or locally waterlogged areas may be reducing.

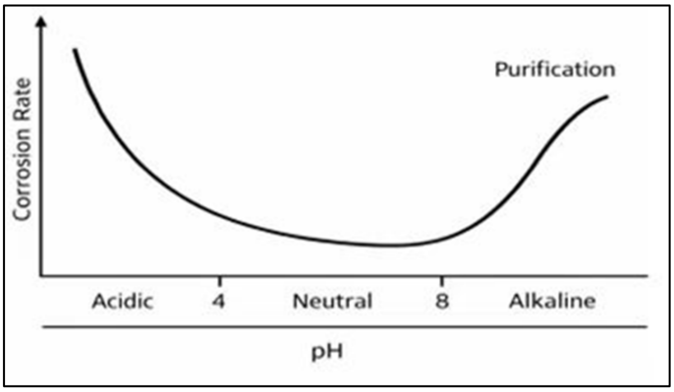

Figure 3 Effect of soil pH on copper corrosion rate

5.2. Alloy intrinsic factors

5.2.1. Chemical Composition

Tin Content: Affects the alloy phase composition (α phase, α+δ phase eutectoid, etc.). High-tin bronzes (e.g., containing 15-25% tin) are generally more resistant to uniform corrosion, but the δ phase ($Cu_{31}Sn_8$) is brittle and prone to selective corrosion [27].

Lead Content: Ancient bronzes often contained lead. Lead is not soluble in copper and is distributed in fine particles. The presence of lead may form micro-galvanic cells (lead usually dissolves preferentially as the anode), but it may also fill casting pores, or its corrosion products (e.g., $PbSO_4$) may have a certain filling/blocking effect [37].

Impurity Elements (As, Sb, Ni, Fe, etc.): The effect on corrosion resistance is complex and depends on the element type, content, and form of existence [1].

Microstructure: Grain size, phase distribution, segregation, inclusions, casting defects (porosity, shrinkage) [4] all affect the initiation and propagation path of corrosion [16]. For example, corrosion tends to occur preferentially around grain boundaries, phase boundaries, and inclusions.

Processing conditions: Residual stress introduced by cold working increases the energy of the metal, enhancing its corrosion susceptibility and potentially leading to stress corrosion cracking (although relatively rare in soil environments).

5.3. Buried environmental factors

- Burial depth: Affects the stability and gradient of temperature, humidity, oxygen concentration, and pressure [7].
- Drainage conditions: Affect the stability of soil moisture content and the frequency of wet-dry cycles [32].

Temperature: Increased temperature usually accelerates chemical reactions and diffusion processes, thereby increasing the corrosion rate (within a certain range) [7].

- Contact with other materials: Contact with more inert materials (stone tools) or more reactive metals (iron tools) may form macroscopic electro couples, accelerating or inhibiting corrosion [7].
- Human disturbances: Such as agricultural cultivation (altering soil structure, introducing fertilizers and pesticides), engineering construction, etc.

6. Conclusions and Outlook

The corrosion of tin bronze in red soil environments is a complex geochemical and electrochemical process driven by the interaction between the unique strong acidity of red soil, its high content of iron and aluminum oxides, complex water and air conditions, and the specific ions and microbial activities present therein, and the inherent material properties of the bronze alloy itself. Compared to neutral or alkaline soils, red soil environments significantly accelerate the overall corrosion rate of bronze, alter the types of corrosion products (making it difficult to form a stable carbonate protective layer, and easily forming oxides and chlorides, etc.), and often lead to more severe localized corrosion and unique corrosion morphologies (such as tin enrichment and tight bonding of soil rust, etc.).

Although our understanding of bronze corrosion in red soil has deepened in recent years through the analysis of unearthed artifacts and laboratory simulations, many challenges and unresolved issues remain: The microscopic interface process mechanisms urgently need to be elucidated: The specific interactions (adsorption, ion exchange, catalysis, galvanic effect, etc.) between the highly reactive iron and aluminum oxide/hydroxide colloids in red soil and the bronze corrosion product layer, and their quantitative impact on the corrosion process, remain unclear. Higher resolution in-situ and dynamic characterization techniques (such as environmental scanning electron microscopy, atomic force microscopy, and synchrotron radiation microarea analysis) are needed to reveal the chemical and physical processes in the interfacial microarea[38].

Microbial mechanisms of action (MIC) need further investigation: The structure of microbial communities in the acidic environment of red soil and their specific roles in bronze corrosion (especially the mechanisms and contribution rates of acidophilic bacteria and iron-cycling-related bacteria) still need to be systematically studied using metagenomics, metabolomics, and electrochemical methods[35].

1Long-term corrosion kinetic models need to be established: Currently, most are short-term simulation experiments or analyses based on the current situation. How to establish a multi-physics coupling model that can comprehensively consider the dynamic changes of multiple factors (pH, eh, moisture, temperature, ions, and microorganisms) in red soil and predict the corrosion evolution trend of bronzes on a scale of hundreds or thousands of years is an important direction and challenge for future research [39].

Insufficient research on the differences among red soil subclasses: Red soils of different parent materials and developmental stages (such as iron-rich red soil and siliceous red soil) have different physicochemical properties, and their influence on bronze corrosion patterns and degrees may differ, requiring more refined classification studies.

Urgent need for targeted protection technology development: Existing bronze protection methods (such as corrosion inhibitor treatment and sealing) are mostly developed based on general environments. Given the characteristics of red soil corrosion (strong acidity, potential chloride ion risk, tight soil-rust bonding, etc.), the development of new, targeted protection materials and technologies that are environmentally friendly, durable, and compatible with the condition of red soil-excavated artifacts (such as technologies that can neutralize acidic microenvironments, effectively inhibit chloride ion activity, or safely remove the soil-rust bonding layer) is an urgent need in cultural relic protection practice[40].

In conclusion, future research should place greater emphasis on interdisciplinary integration (archaeology, materials science, chemistry, soil science, microbiology, geology, and other disciplines), strengthen the application of advanced analytical techniques and simulation methods, and dedicate itself to multi-scale and systematic research, from microscopic mechanisms to macroscopic laws, and from short-term effects to long-term evolution, in order to comprehensively reveal the mysteries of tin bronze corrosion in the special environment of red soil, and provide a more scientific and effective basis for protecting these precious human cultural heritages.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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