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Environmental Fate and Corrosion Inhibition Performance of Benzotriazole-Based Compounds: A Sustainability Perspective

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Abstract*:* Benzotriazole-based compounds are among the most widely used corrosion inhibitors in industrial systems because of their remarkable efficiency in protecting copper, steel, and mixed-metal surfaces. However, increasing environmental concerns regarding persistence, toxicity, and bioaccumulation have raised questions about their long-term sustainability. This research paper examines the corrosion inhibition performance, environmental occurrence, degradation pathways, ecotoxicological effects, and sustainable alternatives of benzotriazole derivatives. The study integrates findings from recent environmental and electrochemical investigations and evaluates the balance between corrosion protection efficiency and ecological safety. Results indicate that benzotriazole compounds exhibit inhibition efficiencies exceeding 90% under optimized conditions, but their persistence in aquatic systems and resistance to biodegradation present environmental risks. Sustainable strategies including biodegradable inhibitors, nanostructured delivery systems, and advanced oxidation treatment technologies are discussed as future directions for green corrosion science.

Keywords: Benzotriazole; Corrosion inhibition; Environmental fate; Sustainability; Ecotoxicology; Biodegradation; Copper corrosion; Green corrosion inhibitors; Advanced oxidation processes; Nanostructured inhibitors; Aquatic toxicity; Surface adsorption; Industrial corrosion protection; Environmental pollution; Sustainable chemistry.

1. Introduction

Corrosion is a major challenge faced by modern industries because it gradually destroys metallic materials through electrochemical reactions with the surrounding environment. The deterioration of metals not only reduces the lifespan and reliability of industrial equipment but also creates serious economic losses worldwide. Industries such as oil and gas, marine engineering, transportation, construction, and power generation spend billions of dollars annually on corrosion prevention and maintenance. In addition to economic damage, corrosion can also result in environmental pollution, industrial accidents, and safety hazards, making corrosion control an important area of scientific and industrial research.

To reduce corrosion-related problems, industries commonly use corrosion inhibitors that form protective barriers on metal surfaces. Among these inhibitors, benzotriazole (BTAH) and its derivatives are considered highly effective, particularly for copper and copper-alloy systems. Benzotriazole molecules adsorb strongly onto metal surfaces and create stable protective films that block corrosive agents such as oxygen, moisture, and chloride ions. This protective mechanism significantly decreases both anodic and cathodic electrochemical reactions, thereby reducing corrosion rates and extending the operational life of industrial equipment.

The high inhibition efficiency and chemical stability of benzotriazole-based compounds have led to their widespread application in cooling water systems, heat exchangers, automotive antifreeze formulations, electronic industries, and marine structures. Various derivatives such as tolyltriazole, hydroxybenzotriazole, and chlorobenzotriazole have also been developed to improve corrosion resistance under different environmental conditions. Research studies have shown that these compounds can achieve inhibition efficiencies above 90% when used under optimized conditions, demonstrating their industrial importance in corrosion science and materials engineering.

Despite these advantages, benzotriazole compounds have become a growing environmental concern because of their persistence and resistance to natural degradation processes. Large quantities of these chemicals enter the environment through industrial wastewater, urban runoff, aircraft de-icing fluids, and domestic sources. Once released into aquatic systems, benzotriazoles are difficult to remove through conventional wastewater treatment methods. Their high mobility and low biodegradability allow them to accumulate in rivers, lakes, groundwater, sediments, and even drinking water supplies. Scientific studies have also indicated potential toxic effects on aquatic organisms, including algae, fish, and microorganisms.

In recent years, increasing emphasis on environmental sustainability has encouraged researchers to evaluate the balance between corrosion protection performance and ecological safety. Sustainable corrosion science now focuses on developing environmentally friendly alternatives that provide high inhibition efficiency with lower toxicity and better biodegradability. Advanced oxidation processes, nanotechnology-based controlled release systems, plant-derived inhibitors, and green chemistry approaches are being investigated as potential solutions to minimize environmental risks. Therefore, understanding the environmental fate and corrosion inhibition performance of benzotriazole-based compounds is essential for designing safer and more sustainable corrosion protection technologies for future industrial applications.

2. Objective of the Study

1. To analyze the corrosion inhibition performance of benzotriazole compounds.
2. To examine the environmental fate and transport mechanisms of benzotriazoles.
3. To evaluate toxicity and ecological impacts.
4. To discuss sustainable approaches and green alternatives.
5. To provide future recommendations for environmentally safer corrosion inhibition technologies.

3. Chemical Structure and Properties of Benzotriazole

Benzotriazole is a heterocyclic aromatic compound containing three nitrogen atoms fused with a benzene ring.

Molecular Information

Property	Value
Chemical Formula	C6H5N3
Molecular Weight	119.12 g/mol
Appearance	White crystalline powder
Solubility	Moderately soluble in water
pKa	8.2
Main Application	Corrosion inhibition

Structural Formula

$C_6H_5N_3$

Benzotriazole derivatives include:

- Tolyltriazole
- Hydroxybenzotriazole

- Chlorobenzotriazole
- Benzotriazole UV stabilizers

These derivatives exhibit varying corrosion inhibition and environmental behaviors depending on substituent groups.

4. Mechanism of Corrosion Inhibition

Benzotriazole inhibits corrosion primarily through adsorption onto metal surfaces.

Adsorption Mechanism

The inhibitor molecules interact with metal surfaces through:

- Lone pair electrons on nitrogen atoms
- π-electron interactions
- Formation of metal-inhibitor complexes

For copper surfaces, the mechanism can be represented as:

$$\mathrm{Cu} + \mathrm{BTAH} \rightarrow \mathrm{Cu(BTA)} + \mathrm{H}^+$$

The resulting polymeric Cu(I)-BTA film acts as a protective barrier against oxygen, chloride ions, and moisture.

5. Corrosion Inhibition Performance

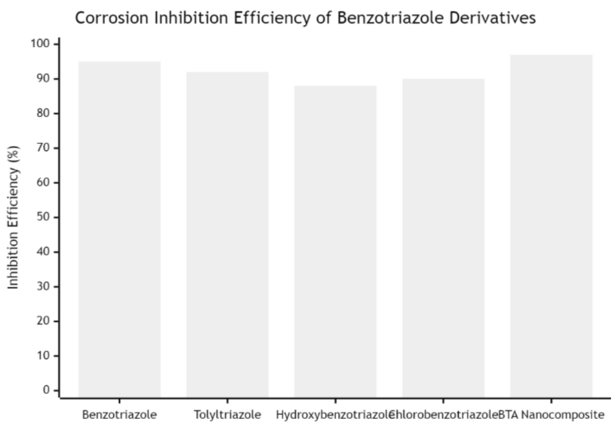
Table 1: Corrosion Inhibition Efficiency of Benzotriazole Derivatives

Compound	Metal Surface	Medium	Concentration	Inhibition Efficiency (%)
Benzotriazole	Copper	NaCl Solution	0.01 M	95
Tolyltriazole	Brass	Seawater	0.005 M	92
Hydroxybenzotriazole	Mild Steel	HCl	0.02 M	88
Chlorobenzotriazole	Stainless Steel	Acidic Medium	0.015 M	90
BTA Nanocomposite	Marine Steel	Artificial Seawater	0.01 M	97

Data compiled from recent corrosion studies.

6. Graphical Representation Of Corrosion Inhibition

Graph 1: Inhibition Efficiency of Different Benzotriazole Compounds



The graph demonstrates that nanostructured benzotriazole systems show the highest inhibition performance due to controlled release and improved surface coverage.

7. Environmental Fate of Benzotriazoles

Benzotriazoles enter the environment through:

- Industrial effluents
- Cooling water discharge
- Aircraft de-icing fluids
- Household detergents
- Automotive antifreeze systems

Environmental Distribution

Environmental Compartment	Typical Concentration
Surface Water	ng/L – µg/L
Wastewater	µg/L
Sediments	ng/g
Groundwater	ng/L
Drinking Water	trace levels

Because of high polarity and water solubility, benzotriazoles are highly mobile in aquatic environments and resistant to conventional wastewater treatment.

8. Environmental Transformation and Degradation

Benzotriazoles undergo:

- Photodegradation
- Biodegradation
- Oxidative degradation
- Hydrolysis

However, biodegradation is generally slow.

Photochemical Degradation

Experimental studies show photochemical half-lives between 1.3–1.8 days under simulated sunlight conditions.

Advanced Oxidation Processes (AOPs)

Effective treatment methods include:

- Ozonation
- UV/H_2O_2
- Photo-Fenton process
- Electrochemical oxidation

These techniques transform benzotriazoles into smaller, less toxic compounds such as phenols and carboxylic acids.

9. Ecotoxicological Impacts

Table 2: Ecological Effects of Benzotriazole Compounds

Organism	Observed Effect	Toxicity Level
Algae	Growth inhibition	Moderate
Fish	Endocrine disruption	Moderate
Daphnia	Reduced mobility	Low to moderate
Bacteria	Enzyme inhibition	Moderate
Aquatic Plants	Reduced photosynthesis	Moderate

Studies suggest chronic exposure may produce:

- Neurotoxicity
- Hepatotoxicity
- Endocrine disruption
- Carcinogenic risks

10. Sustainability Perspective

The sustainability assessment of benzotriazole-based inhibitors involves balancing:

- Corrosion protection efficiency
- Environmental persistence
- Human health risks
- Waste treatment costs
- Regulatory compliance

Advantages

- High inhibition efficiency
- Low dosage requirements
- Strong adsorption behavior
- Compatibility with industrial systems

Limitations

- Poor biodegradability
- Aquatic toxicity
- Persistence in wastewater
- Potential bioaccumulation

11. Green and Sustainable Alternatives

Researchers are investigating environmentally safer corrosion inhibitors including:

Natural Inhibitors

- Plant extracts

- Amino acids
- Biopolymers
- Essential oils

Smart Nanomaterials

Layered double hydroxides loaded with benzotriazole provide controlled inhibitor release and reduced environmental exposure.

Ionic Liquids and Hybrid Systems

Eco-friendly ionic liquid inhibitors demonstrate high efficiency with reduced toxicity.

12. Future Research Directions

Future research should focus on:

1. Development of biodegradable benzotriazole analogues.
2. Life-cycle assessment of corrosion inhibitors.
3. Green synthesis routes.
4. Nanotechnology-based controlled release systems.
5. Real-time environmental monitoring.
6. Integration of AI and computational chemistry for inhibitor design.

13. Conclusion

Benzotriazole-based compounds remain among the most effective corrosion inhibitors for copper and steel systems. Their excellent adsorption properties and film-forming abilities provide outstanding corrosion protection in industrial and marine environments. However, their environmental persistence, mobility, and ecotoxicological effects raise serious sustainability concerns.

Modern environmental regulations and sustainability goals require the development of safer and greener corrosion inhibition technologies. Advanced oxidation treatments, nanostructured delivery systems, and biodegradable inhibitors represent promising strategies for reducing ecological risks while maintaining industrial performance.

The future of corrosion science depends on integrating high inhibition efficiency with environmental compatibility, enabling sustainable material protection for modern industries.

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