CORROSION INHIBITORS

A HANDBOOK WITH CONTEMPORARY INSIGHTS

Editors:
Anjaneyulu Bendi
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Corrosion Inhibitors: A Handbook with Contemporary Insights

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CONTENTS

FOREWORD i

PREFACE iii

LIST OF CONTRIBUTORS v

CHAPTER 1 INTRODUCTION 1

Prabhjot Kaur, Urmila Berar and *Neera Raghav*

INTRODUCTION 1

Understanding Corrosion: Implications for Society and the Economy 2

Forms of Corrosion 4

Uniform Corrosion 6

Pitting Corrosion 6

Crevice Corrosion 6

Galvanic Corrosion 6

Intergranular Corrosion 6

Stress Corrosion Cracking (SCC) 7

Erosion Corrosion 7

Microbiologically-Influenced Corrosion (MIC) 7

Atmospheric Corrosion 7

Necessity and Role of Corrosion Inhibitors 8

Advantages of Corrosion Inhibitors 8

Types of Corrosion Inhibitors 9

Mechanism of the Corrosion Inhibition 11

Adsorption Mechanism 12

Formation of Protective Films 12

Electrochemical Reaction Suppression 12

Surface Charge and Double-layer Modification 12

Electron Donation and Molecular Interactions 13

pH Modulation 13

Synergistic Effects and Hybrid Systems 13

Mechanisms in Green Corrosion Inhibitors 13

Role of Nano-inhibitors and Smart Inhibitors 14

Factors Influencing Inhibition Efficiency 15

Evaluation of Corrosion Inhibitors 15

Gravimetric (Weight Loss) Method 15

Electrochemical Methods 16

Surface Analysis Techniques 16

Thermodynamic and Kinetic Studies 17

Computational and Theoretical Approaches 17

Artificial Intelligence and Machine Learning Approaches 18

Field Testing and Real-world Validation 18

Challenges in Inhibitor Evaluation 18

Selection of Corrosion Inhibitors 19

Key Considerations for Selection 19

Metal Type and Environmental Conditions 19

Modern Trends in Inhibitor Selection 22

Corrosion Inhibitor Delivery Systems 22

..... 22

CONCLUSION 26

LIST OF ABBREVIATIONS 26

CONSENT FOR PUBLICATION 27
ACKNOWLEGDEMENTS 27
REFERENCES 27

CHAPTER 2 CLASSIFICATION OF CORROSION INHIBITORS 32
Vipra Kamboj, Gopal Ji and *Bindu Mangla*
INTRODUCTION 32
Classification of Inhibitors 33
Volatile Inhibitors 33
Passivating or Anodic Inhibitors 35
Cathodic Inhibitors 37
Hybrid Inhibitors 38
Organic Inhibitors 39
Inorganic Inhibitors 42
Precipitation Inhibitors 44
Green Inhibitors 46
RECENT TRENDS AND FUTURE SUGGESTIONS 48
CONCLUSION 51
LIST OF ABBREVIATIONS 51
CONSENT FOR PUBLICATION 52
ACKNOWLEGDEMENTS 52
REFERENCES 52

CHAPTER 3 CHEMISTRY OF CORROSION INHIBITORS FOR PROTECTING COPPER AND ITS ALLOYS 56
Nisha Sharma and *Rashmi Pundeer*
INTRODUCTION 56
STRUCTURAL AND FUNCTIONAL CHARACTERISTICS OF COPPER 57
ESSENTIALITY AND RAMIFICATIONS OF THE COPPER INDUSTRY 58
ROLE OF CORROSION INHIBITORS FOR PROTECTING COPPER AND ITS ALLOYS 59
Intrinsic Anti-corrosive Characteristics and Failure Mechanism of Copper and its Alloys ... 59
Types of Corrosion of Copper and its Alloys 60
Corrosion of Copper and Alloys in Varied Environments 60
Stress Corrosion Cracking (SCC) of Copper and its Alloys 61
Factors Affecting SCC in Copper and Alloys 62
Atmospheric Corrosion 62
Microbiologically-induced Corrosion 63
The Remedial Actions to Extend Copper-based Alloys 63
Corrosion Diminution Techniques for Copper and Alloys 63
CORROSION INHIBITORS FOR COPPER 69
Benzotriazoles as Efficient Corrosion Inhibitors 70
Imidazoles/Benzimidazoles as Corrosion Inhibitors 71
Green Corrosion Inhibitors 77
CONCLUSION 81
LIST OF ABBREVIATIONS 81
CONSENT FOR PUBLICATION 82
ACKNOWLEDGEMENTS 82
REFERENCES 82

CHAPTER 4 CHEMISTRY OF CORROSION INHIBITORS FOR PROTECTING ALUMINIUM AND ITS ALLOYS 88
Yankita, Vishaka Chauhan, Chinmay and *Anjaneyulu Bendi*

INTRODUCTION 89
Structural and Functional Characteristics of Aluminium 89
Essentiality and Ramifications of the Aluminium Industry 90
Role of Corrosion Inhibitors in Protecting Aluminium and its Alloys 91
CHEMISTRY OF CORROSION INHIBITORS FOR PROTECTING ALUMINIUM AND ITS ALLOYS 93
BENEFITS AND ADVERSE EFFECTS OF ASYMMETRIC SYNTHESIS ON MEDICINAL DRUGS 108
Benefits 108
Adverse Effects 108
CONCLUSION 109
LIST OF ABBREVIATIONS 109
CONSENT FOR PUBLICATION 110
ACKNOWLEDGMENTS 110
REFERENCES 110

CHAPTER 5 ROLE OF BIOMASS CORROSION INHIBITORS IN METAL CORROSION INHIBITION 117
Sahil, Surender Kumar, Versha and *Abhishek Sharma*
INTRODUCTION 118
Importance of Corrosion Control in Various Industries 119
Traditional Methods of Corrosion Inhibition 120
Drawbacks of Synthetic Corrosion Inhibitors 123
Environmental and Toxicity Concerns 123
High Cost 123
Limited Effectiveness in Certain Conditions 123
Dependency on Concentration and Maintenance 124
Potential for Side Effects 124
Non-biodegradability 124
Interactions with Other Chemicals 124
BIOMASS CORROSION INHIBITORS (BCIS) 125
Benefits of Biomass Corrosion Inhibitors Over Traditional Methods 125
Mechanism of Biomass-based Corrosion Inhibition 126
Physical Adsorption 126
Chemisorption 128
Film-forming Adsorption 130
Adsorption Isotherm Modeling 132
Types of Biomass Corrosion Inhibitors 133
Plant-based Inhibitors 133
Microorganism-based Inhibitors 134
Amino Acid-based Inhibitors 135
Effectiveness of Biomass Corrosion Inhibitors in Different Environments 136
Environmental and Economic Aspects of Biomass Corrosion Inhibitors 138
REPRESENTATIVE CASE STUDIES OF BIOMASS CORROSION INHIBITORS (BCIS) 140
CHALLENGES AND LIMITATIONS OF BIOMASS CORROSION INHIBITORS 142
FUTURE DIRECTIONS IN BIOMASS CORROSION INHIBITION RESEARCH 145
CONCLUSION 147
LIST OF ABBREVIATIONS 147
CONSENT FOR PUBLICATION 148
ACKNOWLEDGEMENTS 148

REFERENCES 148

CHAPTER 6 ADVANCEMENTS IN THE SYNTHESIS OF CORROSION INHIBITORS 155
Mahesh Kumar Purohit, Adem Balakrishna, P. Lakshmi Praveen and *D. S. Ramakrishna*
INTRODUCTION 155
SYNTHETIC APPROACHES TO PRODUCE ORGANIC PRODUCTS CONTAINING CORROSION INHIBITORY PROPERTIES 157
ANTI-CORROSIVE PERFORMANCE OF SYNTHESIZED COMPOUNDS TO CONNECT THE SYNTHESIS TO PRACTICAL OUTCOMES 171
ENVIRONMENTAL CONCERNS OF HAZARDOUS REAGENTS WITH SPECIFIC MITIGATION STRATEGIES 172
TABLE SUMMARIZING SYNTHETIC METHOD, YIELD, AND ENVIRONMENTAL IMPACT 172
CONCLUSION 173
LIST OF ABBREVIATIONS 174
CONSENT FOR PUBLICATION 175
ACKNOWLEGDEMENTS 175
REFERENCES 175

CHAPTER 7 ROLE OF NANOMATERIALS AND NANOCOMPOSITES IN CORROSION INHIBITION 179
Riya, Garima Pandey and *Ravi Tomar*
INTRODUCTION 180
Corrosion Inhibitors 180
Broad Classification of Corrosion Inhibitors 181
A. Based on the Mechanism of Action 181
1. Anodic Inhibitors 181
2. Cathodic Inhibitors 182
3. Mixed Inhibitors 182
B. Based on Application Method 182
1. Admixture-Type Inhibitors 182
2. Surface-Applied or Migrating Corrosion Inhibitors (MCI) 182
NANOMATERIALS 182
Classification of Nanomaterials 184
Organic Nanoparticles 185
Inorganic Nanoparticles 185
Carbon-based Nanoparticles 188
Core-shell Nanomaterials 189
Based on Origin 190
Based on Structure or Composition 190
Based on Dimensionality 191
Based on Pore Size 191
Based on Potential Toxicity 191
Synthesis of Nanomaterial 192
Top-down Approaches 192
Mechanical Milling 192
Lithography 193
Laser Ablation 193
Bottom-up Approaches 193
Chemical Vapor Deposition (CVD) 193
Sol-gel Synthesis 193

Co-precipitation 194
Hydrothermal and Solvothermal Methods 194
Microemulsion Technique 194
Green Synthesis 194
NANOMATERIALS AS CORROSION INHIBITORS 194
Metal/Metal Oxides as Corrosion Inhibitors 195
Quantum Dots as Corrosion Inhibitors 195
Nanotubes and Nano-fibres as Corrosion Inhibitors 195
Nanocomposites as Corrosion Inhibitors 196
Graphene-based Nanocomposites 197
Carbon Nanotube (CNT)-based Nanocomposites 197
Metal Oxide Nanoparticle-reinforced Nanocomposites 198
Layered Double Hydroxide (LDH) Nanocomposites 198
Metal-organic Framework (MOF) Nanocomposites 199
Distinction between Organic and Green Inhibitors 199
Conductive Polymer Nanocomposites 199
Hybrid Nanocomposites 200
CHALLENGES FACED BY NANO-COATED SURFACES AND THEIR MITIGATION STRATEGIES 201
CONCLUSION 204
CONSENT FOR PUBLICATION 204
ACKNOWLEDGMENTS 204
REFERENCES 204

CHAPTER 8 APPLICATIONS OF CORROSION INHIBITORS 212
Raman Singh, Aarti Dwivedi and *Kuldeep Singh*
INTRODUCTION 212
ELECTRONICS INDUSTRY 213
Protecting Sensitive Components 213
Volatile Corrosion Inhibitors (VCI) 214
Conformal Coatings with Embedded Inhibitors 214
Green Corrosion Inhibitors for Electronics 215
Advanced Delivery Systems 215
PETROLEUM INDUSTRY 216
Combating Corrosion in Extreme Environments 216
Upstream Applications 216
Pipeline Protection 216
Refinery Applications 217
Emerging Trends in Inhibitors of the Petroleum Industry 217
NATURAL GAS INDUSTRY 218
Specialized Challenges in Natural-gas Systems 218
Pipeline Internal Corrosion Control 219
Gas Processing Facilities 219
Dual-function Inhibitors for Natural-gas Systems 220
Environmental Sustainability in Natural-gas Inhibitors 220
MILITARY EQUIPMENT 221
Protecting Strategic Assets in Hostile Environments 221
Naval Applications 221
Aviation and Aerospace 222
Ground Vehicles and Field Equipment 222
Advanced Inhibitor Technologies for Military Applications 223

COATINGS, PAINTS, AND FILMS 223
The First Line of Defense 223
Types of Inhibitor-enriched Coatings 224
Inhibitor Release Mechanisms 224
Green Innovations in Inhibitive Coatings 226
Industrial Applications 226
COOLING WATER SYSTEMS 227
Manage Complex Corrosion Challenges 227
Types of Cooling Water Inhibitors 227
Considerations Specific to the Cooling Tower 228
Closed System Treatment 229
Green Inhibitors for Cooling Water Systems 229
Monitoring and Control Strategies 230
SUMMARY OF DIFFERENT CORROSION INHIBITOR TYPES AND APPLICATION 230
CONCLUSION 232
LIST OF ABBREVIATIONS 233
CONSENT FOR PUBLICATION 233
ACKNOWLEGDEMENTS 233
REFERENCES 233
SUBJECT INDEX 241

FOREWORD

It is a great pleasure to write the foreword to ***Corrosion Inhibitors: A Handbook with Contemporary Insights*** edited by ***Dr. Anjaneyulu Bendi, Prof. (Dr.) Rashmi Pundeer, and Prof. (Dr.) Neera Raghav***. The editors are excellent scientists with a broad experience in many fields of chemistry. Their intellectual accomplishments, depth of experience, and continuous devotion to scientific progress have gained them tremendous recognition and esteem in the academic and research communities.

Corrosion is a major and costly problem for contemporary industries, impacting the lifetime, safety, dependability, and economic viability of materials and infrastructure. Hence, the search for new, efficient, and environmentally benign corrosion inhibitors has become increasingly important in fundamental research and practical applications. The selectivity and efficiency of the inhibitors are especially important for the success of corrosion-control schemes for different materials and diverse operating situations.

Recent developments in chemistry, materials science, and surface engineering have profoundly changed our approach to corrosion protection. New technologies, such as nanotechnology, smart and sensitive coatings, and sophisticated molecular design, along with modern synthetic techniques, have opened new avenues for the development of highly efficient and sustainable protection systems. Such improvements allow for more accurate control of corrosion processes and the design of materials and coatings with improved durability, usefulness, and environmental compatibility.

Against this continuously expanding scientific backdrop, ***Corrosion Inhibitors: A Handbook with Contemporary Insights*** presents a timely and thorough overview of current advances in corrosion science and inhibition technology. The book integrates up-to-date knowledge and new insights, with specific focus on molecular and technical advancements that are transforming the field of material protection. Its chapters address the potential of new corrosion inhibitors and innovative protective techniques, focusing on their ability to deliver solutions that are more efficient, long-lasting, cost-effective, and environmentally friendly.

The importance of this volume extends beyond a mere record of current scientific advances. The development of improved corrosion-control technology is becoming increasingly important in light of global concerns, such as sustainability, resource efficiency, infrastructure durability, and environmental responsibility. This book bridges fundamental scientific understanding with emerging technical approaches to offer useful insights for addressing corrosion-related challenges across a broad range of industrial applications.

I am confident that ***Corrosion Inhibitors: A Handbook with Contemporary Insights*** will be a valuable source of information for researchers, academicians, students, industry professionals, engineers, and policymakers working in the fields of corrosion science, materials chemistry, surface engineering, and related disciplines. I further believe that the viewpoints discussed in this volume will offer fertile ground for new ideas, foster multidisciplinary research, and contribute substantially to the development of next-generation sustainable corrosion-protection systems.

I applaud the editors and contributing authors on this essential and timely publication. I do hope that this book will earn the recognition it deserves in the scientific and professional communities and will be an inspiration for further studies and innovations in the important field of corrosion prevention and material protection.

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PREFACE

Interdisciplinary advancements involving aspects of chemistry, materials science, nanotechnology, and environmental engineering are shaping strategies to prevent corrosion. These developments have been useful in the creation of smarter, durable coatings and inhibitors that improve corrosion resistance while lowering operating expenses and associated negative environmental effects. They offer a comprehensive strategy for safeguarding vital infrastructure by fusing state-of-the-art technology with conventional corrosion research, making it more affordable, sustainable, and future-ready for a range of industries.

This book summarizes the most recent experimental research on the creation and use of materials as corrosion inhibitors in the form of ten chapters. The basic knowledge of corrosion, its effects on the economy and society, and its different forms and methods are all covered in detail in **Chapter 1**, along with the importance of corrosion inhibition, inhibitor evaluation techniques, selection standards, and contemporary delivery technologies. **Chapter 2** details the classification of corrosion inhibitors based on their chemical nature, mechanism of action, and application environment.

The chemistry of corrosion inhibitors used to safeguard copper and its alloys is covered in detail in **Chapter 3**, with a focus on the inhibitors' structural compatibility and efficacy, and the industrial importance of copper, its functional characteristics, and the critical role inhibitors play in enhancing its performance and longevity.

In **Chapter 4**, the authors particularly focus on exploring the procedures to safeguard aluminium and its alloys, with an emphasis on how the corrosion inhibitors interact with the unique properties of the metal.

The function of biomass-based corrosion inhibitors in metal protection is covered in detail in **Chapter 5**, along with the need for environmentally friendly substitutes, the different kinds of biomass inhibitors, and how well they work to stop metal corrosion. **Chapter 6** describes the use of natural products in corrosion inhibition, emphasizing environmentally friendly and sustainable solutions with the emphasis on plant extracts, natural polysaccharides, and fruit and vegetable derivatives as effective corrosion inhibitors.

The function of nanoparticles and nanocomposites in corrosion inhibition is covered in detail in **Chapter 7**, which highlights the importance of nanomaterials and engineered nanocomposites in the improvement of corrosion resistance through improved barrier properties and surface interactions. **Chapter 8** details the application of corrosion inhibitors in reinforced concrete, emphasizing their importance in preserving structural integrity and covers various types of inhibitors, the electrochemical injection method (EICI), along with the significance of electrochemical chloride extraction techniques.

In conclusion, the goal of this book is to provide a comprehensive overview of the latest research on corrosion inhibitors and their transformative role in material protection. We aim to engage scholars, engineers, and industry professionals, inspiring them to explore innovative and sustainable solutions for combating corrosion across diverse sectors. Additionally, we believe this book will serve as a valuable resource for researchers, academics, and professionals.

We would like to express our profound appreciation and gratitude to all the contributing authors for their exceptional dedication and expertise in crafting the content of this book. Our heartfelt thanks extend to the publisher and the team involved for their seamless and professional management of the project at every stage, ensuring its timely and successful completion. Finally, we are deeply indebted to our families for their unwavering support, encouragement, and patience throughout this journey, without which this endeavour would not have been possible.

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CHAPTER 1

Introduction

Prabhjot Kaur[1], Urmila Berar[1] and **Neera Raghav[2,*]**

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Abstract: Corrosion, an intricate electrochemical phenomenon, significantly impacts global industries by causing material degradation, economic loss, and safety hazards. This chapter provides a comprehensive overview of corrosion from a chemical perspective, beginning with its fundamental definition and societal implications. Different types of corrosion, such as stress corrosion cracking, galvanic, uniform, pitting, crevice, and intergranular corrosion, are categorised and discussed in a methodical manner. The importance of corrosion inhibitors is examined, with a focus on their requirement, modes of action (such as passivation and adsorption), and contemporary assessment methods (such as surface characterisation and electrochemical impedance spectroscopy). The most recent developments in green inhibitors and innovative delivery methods—such as nanocontainer and microencapsulation-based techniques—are examined to emphasise effective and long-lasting defences. Additionally, choosing parameters for corrosion inhibitors is evaluated, taking into account elements like the type of metal, operating conditions, and environmental impact. In order to facilitate the creation of safer and more resilient materials, this chapter attempts to give readers a comprehensive grasp of corrosion control methods and current research developments through in-depth discussions, tables, and illustrations.

Keywords: Corrosion, Corrosion inhibitors, Green inhibitors, Nano inhibitors.

INTRODUCTION

In the fields of materials research, engineering, management of infrastructure, and protecting the environment, corrosion is a common occurrence that poses serious challenges. In its broadest sense, it refers to the degradation of materials—especially metals—due to electrochemical or chemical interactions with their surroundings [1, 2]. Corrosion can take many different forms, including crevice corrosion, pitting, SCC, galvanic corrosion, and corrosion driven by microbes. It

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is caused by the thermodynamic preference of metals to revert to more stable, oxidised forms. While commonly associated with visible rusting, corrosion encompasses a wide range of subtle and complex degradation mechanisms.

In addition to its practical consequences for a wide range of industries, including transportation, construction, energy generation, water treatment, marine operations, and healthcare, corrosion research is essential from a scientific perspective. When materials' mechanical integrity and dependability are compromised by corrosion, significant financial losses, environmental harm, and safety risks result. The dire repercussions of uncontrolled corrosion are highlighted by historical instances of public health crises, industrial tragedies, and structural failures [3, 4].

Many of the effects of corrosion have been lessened by industry thanks to developments in monitoring systems, preventive measures, and our understanding of how corrosion occurs. However, corrosion is still a persistent and complicated problem as infrastructure ages, climatic conditions change, and technology demands rise. The necessity for continuous research and innovation is highlighted by emerging concerns, such as the impact of climate change on metal durability, the creation of green corrosion inhibitors, and the deployment of smart monitoring systems [5, 6].

This chapter provides a thorough analysis of corrosion with a focus on its effects on society and the economy. Effective corrosion control is crucial for maintaining structural resilience, environmental sustainability, and economic security, as can be shown by looking at the basic mechanics and extensive impacts of corrosion.

Understanding Corrosion: Implications for Society and the Economy

The natural process of corrosion causes materials, especially metals, to deteriorate through chemical or electrochemical reactions with ambient elements like oxygen, moisture, and contaminants. Fundamentally, corrosion is a reflection of metals' thermodynamic propensity to return to their more stable, oxidised states, which weakens their structural integrity and functional capabilities. Corrosion includes several different mechanisms, including pitting, corrosion caused by microbes (MIC), SCC, galvanic corrosion, and crevice corrosion, although it is most usually linked to the rusting of steel [7, 8].

Corrosion is much more important than just material degradation. It jeopardises mechanical strength, operational dependability, and safety in vital industries like healthcare, energy, transportation, construction, and marine operations. The financial cost is huge; according to the NACE (National Association of Corrosion Engineers), corrosion-related losses worldwide surpass $2.5 trillion per year, or

roughly 3-4% of global gross domestic product (GDP). An estimated $276 billion is spent annually on corrosion in the United States alone, which includes both direct expenditures like repairs and indirect costs like lost productivity and environmental cleanup [9, 10].

The socioeconomic effects of corrosion are significant, especially when infrastructure is jeopardised. Failures in water distribution systems, railroads, bridges, and highways can endanger public safety and cause disastrous accidents. The 1967 collapse of the Silver Bridge, which was ascribed to structural failure brought on by corrosion, serves as a sobering reminder of the risks associated with improper maintenance. These days, the need for ongoing monitoring and efficient corrosion control techniques is highlighted by the ageing infrastructure in both developed and developing countries [9 - 11].

Corrosion presents particular difficulties in the energy industry. Oil and gas transportation pipelines are especially susceptible to internal and external corrosion, which can result in dangerous spills and environmental catastrophes. The severe sea conditions also hasten the deterioration of wind turbines and offshore platforms. Despite substantial investments made by businesses in corrosion-resistant materials, protective coatings, and stringent maintenance procedures, controlling corrosion is still a major operational and financial burden.

In addition to structural and financial issues, corrosion poses significant environmental hazards. Long-term ecological harm can arise from the leakage of harmful compounds into soil and water bodies due to pipeline or storage tank failures. The environmental consequences are further highlighted by oil spills and chemical leaks, which are frequently made worse by corrosion. The environmental burden is further increased by the significant resource consumption and carbon emissions associated with the development of replacement materials for corroded infrastructure.

The effects of corrosion are not exempt from public health concerns. One prominent instance is the Flint Water Crisis, in which lead pollution resulted from poor corrosion control in the public water supply system, putting thousands of citizens in danger and having serious health effects, particularly for children. Similar to this, corrosion-related malfunctions in hospital systems and medical equipment might jeopardise patient safety, highlighting the necessity of strict corrosion management in all industries [12, 13].

Corrosion management calls for a proactive, multidimensional strategy. Using corrosion-resistant materials, such as titanium alloys, stainless steels, and sophisticated polymers, as well as applying protective coatings and corrosion inhibitors, are examples of preventive measures. Predictive maintenance, non-

CHAPTER 2

Classification of Corrosion Inhibitors

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Abstract: Corrosion is a paramount problem for metals because it destroys the useful and functional properties of metals. Due to this, huge amounts of money go to waste, and loss of human life occurs. It is not only one nation's problem but also the whole world's. Hence, various methods have been developed to combat it, like cathodic protection, coatings, *etc*. Out of all methods, the use of inhibitors has been proven to be one of the most effective methods for corrosion inhibition. Inhibitors generally function by creating a protective layer on the metal surface *via* adsorption. However, its functioning can slightly differ according to the type of inhibitor used. In this chapter, the corrosion problem, the basics of inhibitors, types of corrosion inhibitors, their working mechanisms, and recent trends in corrosion inhibition have been discussed. The summary of the discussion has also been provided at the end of the chapter, highlighting the key points. This will be very useful for the students, research scholars, and beginners working in the area of corrosion inhibition.

Keywords: Classification, Corrosion, Inhibitors, Recent trends, Working mechanism.

INTRODUCTION

Corrosion relates to the degradation of metals due to their thermodynamic instability. To establish thermal equilibrium, metals react with the surroundings and change into their ore form [1]. This conversion may be faster or slower depending upon the metal's resistance and environmental aggressiveness. Hence, corrosion is considered a devil for metals because it destroys their useful properties. Corrosion not only destroys metals but also influences human lives.

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There are many examples in history when corrosion failure caused the loss of huge amounts of money and human lives. In the Silver Bridge collapse (1967), 46 people died, and a loss of millions of dollars occurred [2]. One of the biggest tragedies in India (the Bhopal gas tragedy) occurred in 1984 due to leakage of water through rusty pipes [3]. Around 10000 people died, and many people were affected badly, even after many years since the incident. As per estimation, the USA is spending 39.8 billion USD per year on corrosion control [4]. There are many more incidents that advocate that corrosion must be controlled to avoid money and human losses.

There are various methods available to combat corrosion attacks, like cathodic protection, coatings, and inhibitors [5]. However, the use of inhibitors for corrosion control is one of the best strategies. Inhibitors have been widely used to control corrosion in a number of facilities like large-scale industries, chemical corporations, energy production plants, crude oil refineries, and combined industries [6]. Inhibitors are chemical substances that retard the corrosion of metals in a corrosive medium upon adding them in small amounts [7]. Inhibitors are directly added in corrosive environments and adsorbed on the metal surface, creating a preventive layer around metals. The protective layer segregates the metals from the surroundings and impedes the corrosion attack [8 - 10]. However, the layer formation is influenced by many factors, such as pH, temperature, and aggressiveness of the corrosive solution.

Classification of Inhibitors

Though the adsorption over metal's surface is the key working principle of inhibitors, the adsorption of inhibitors over metals could take place in different ways, controlling different corrosion reactions. Based on this, they can be classified into different categories (Fig. **1**). Each category will be discussed along with its working mechanisms in its respective section in detail.

Volatile Inhibitors

Volatile corrosion inhibitors (VCI) are compounds that can be adsorbed on metals andprevent their damage by being comparatively easilyvolatile at room temperature [6]. It can also be said that VCIs have high vapour pressure and hence are easily vaporised at low temperatures. Whenever the protective layer on a metal surface breaks due to some reason, VCIs are adsorbed on the surface and protect against the attack of aggressive agents (Fig. **2**). Volatile corrosion inhibitors are designed to temporarily safeguard metallic substances in the atmosphere, primarily when they are being stored or transported. Their application takes the form of product-impregnated packaging material, powdery substances, or fluid sprinkling [8].

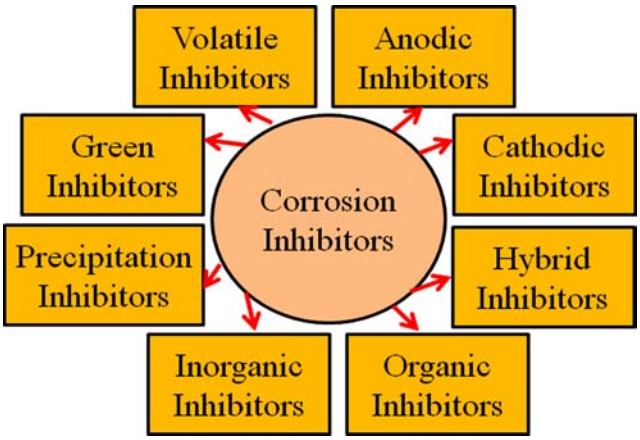

Fig. (1). Classification of corrosion inhibitors.

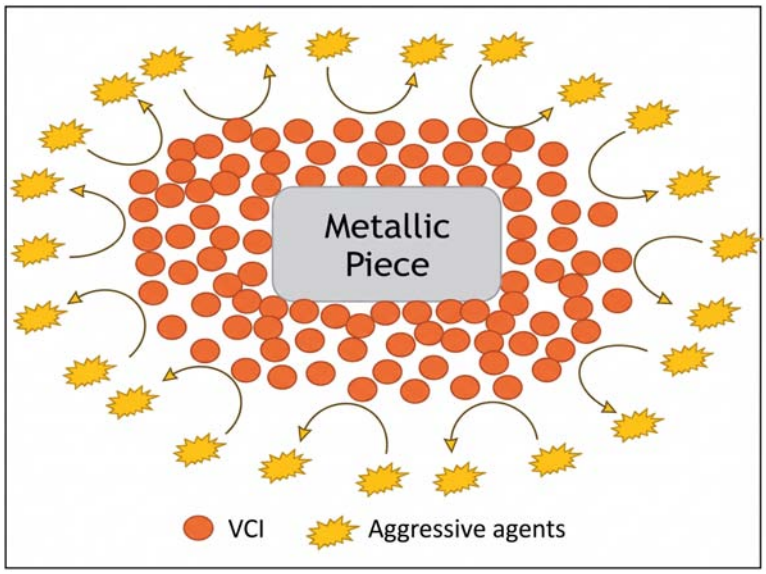

Fig. (2). Working mechanism of volatile corrosion inhibitor. Adopted from Abbout *et al*., [11]. No permission required (Open access).

VCIs are able to lessen the water-soluble characteristics of metal surfaces to extract humidity and substances with hydrophobic characteristics, as the surface of metals under atmospheric corrosion circumstances is always saturated beneath the membrane that conducts corrosion. Only nitrites, benzoates, chromates, *etc.*, were discovered to be used as contact corrosion inhibitors, which are still quite widely reported in the literature. There are also many different types of volatile inhibitors, including the well-known amine-based inhibitors.

CHAPTER 3

Chemistry of Corrosion Inhibitors for Protecting Copper and its Alloys

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Abstract: The extensive utility of copper and its alloys is greatly influenced by different forms of corrosion during their exposure to corrosive environmental conditions like moisture, acids, alkalis, pollutants, *etc*. While they have natural resistance to corrosion by the formation of a protective oxide layer, some harsh conditions, such as mechanical stress, chlorides, and pollutants, can give rise to significant damage. This chapter discusses the deterioration of copper and its alloys due to corrosion in various corrosive environments, along with the important groups employed for the protection of copper as corrosion inhibitors. The main factors affecting the corrosion of copper and copper-based alloys are also emphasized. Structural and functional characteristics of copper are mentioned along with its essentiality and the ramifications of the copper industry. According to the literature, both acidic and alkaline environments are responsible for corroding copper, mainly initiated by oxide formation. The key intention of the present chapter is to present details about the varied environments in which the corrosion of copper and copper-derived alloys can be initiated and compounds used in such environments to prevent corrosive degradation of copper. Various mitigation techniques to protect copper and its alloys from corrosion, especially the use of inhibitors and anticorrosion coatings, are highlighted. A variety of organic compounds, plant extracts, and polymers have shown high efficiency in increasing the corrosion resistance of copper and its alloys. Understanding the utmost corrosion protection efficiency of a particular compound in a specific environment is crucial to selecting the best suitable inhibitor.

Keywords: Copper, Copper alloys, Corrosion, Corrosion inhibitors, Corrosion inhibition efficiency.

INTRODUCTION

Copper is a pertinent material that is widely used because of its thermal, mechanical, and electrical properties; still, it is easily receptive to decay by

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corrosion, especially in acidic environments where its dissolution can occur during the cleaning of industrial equipment [1]. Using certain compounds as corrosion inhibitors is the most employed technique, which can diminish the corrosion rate significantly by preventing the reactions of copper in corrosive media. Corrosion inhibitors are actually the compounds whose presence, even in small concentrations, in corrosive media, effectuates the decrease in reaction rate of metal with the media [2, 3]. These inhibitor compounds can be either inorganic or organic in nature. Inorganic inhibitors cause oxidation of metal to produce a protective layer, thereby obstructing the direct interaction of ions with metal and subsequently decelerating the dissolution process. On the other hand, organic inhibitors require some specific characteristics, like the presence of heteroatoms or double bonds, and a large surface area to effectively enfold the metal surface and protect it from ions responsible for corrosion. In this chapter, we are going to discuss the chemistry of various inhibitors for protecting copper and its alloys from corrosion.

STRUCTURAL AND FUNCTIONAL CHARACTERISTICS OF COPPER

Copper is classified as a metal and chemical element on the periodic table of elements with atomic number 29. Its symbol 'Cu' is adopted from the Latin word 'cuprum'. Cuprum, the Latin name for copper, emerged from the islands of Cyprus (in the eastern Mediterranean Sea) because of its primary source in ancient times. It was also called the "metal of Cyprus" because of its origin from Cyprus. Out of 29 isotopes of copper, only two are stable (^{63}Cu and ^{65}Cu), and the remaining 27 are radioisotopes [4]. ^{63}Cu is the most plentiful isotope of copper, which is accountable for about 69% of naturally found copper. Copper was found to have a face-centred cubic crystal structure. In terms of natural abundance, it ranks fifth in the Earth's crust and is characterized as a metal with a reddish-orange color. However, before oxidation, the actual color of pure copper is pink. The formation of copper oxide (brown) on the surface takes place so fast that any readily available copper will be in a common reddish-brown color. Apart from this, a greenish-blue color can also be developed on copper over time (such as on the Statue of Liberty) due to the formation of copper carbonate.

The natural ores of copper, *i.e.*, a copper sulfide ore (such as chalcopyrite) or a copper oxide ore, are the main sources of copper. To extract copper, these ores are first mined, then crushed and processed. The copper ores are usually located in some countries, such as Chile and Peru in North and South America, as well as in Zambia and the Democratic Republic of Congo in Africa, and in areas like the Ural Mountains in Russia.

Copper is a very useful metal, either in pure or alloy form. The most important alloys of copper are brass, copper-nickel, and bronze. Due to numerous remarkable properties of copper and its alloys, such as good corrosion resistance, excellent electrical and thermal conductivity, malleability, and mechanical workability, they are extensively used in various industries [5, 6]. The extreme importance of copper and its alloys is also displayed by their extensive usability in the production of sheets, wires, and pipelines in power stations, cooling towers, and heat exchangers, electronic industries, marine industries, *etc*. [7, 8]. Copper is also considered a noble metal as it shows significant resistance towards corrosion, which is attributed to the creation of a protective film of oxide on the surface of copper. This protective layer screens the metal from further corrosion in the atmosphere and also in other chemical environments [9, 10].

ESSENTIALITY AND RAMIFICATIONS OF THE COPPER INDUSTRY

The copper industry is essential because of its crucial role in human history, starting from the Industrial Revolution to modern times. While its essentiality extends over technological, economic, and biological domains, on the other hand, its ramifications enclose health, environmental, and socio-economic dimensions. During the Industrial Revolution, various sectors such as the development of the steam engine, textile printing, and sugar production were influenced by copper. The Industrial Revolution depended heavily on copper due to its unique material properties, such as conductivity, resistance to corrosion, and durability [11].The copper industry has progressed to become more energy efficient, competitive, and environmentally sustainable during the last 40 years [12].

Copper is also found to be an essential metal for human health as compared to other nonessential elements. It is important for various biological functions in the body [13 - 16]. It performs a vital role in the catalytic and structural functions of cuproenzymes, the enzymes that require copper to work properly. Both the deficiency as well as excess of copper can lead to health hazards. However, it was suggested that marginal copper deficiency is a more serious public health issue than its excess, necessitating careful risk assessment methodologies. The copper industry faces regulatory scrutiny due to anthropogenic copper release from various industrial activities, which gives rise to environmental risks, leading to soil and water pollution. Health ramifications include gastrointestinal disturbances from excessive intake of copper and conditions like Wilson's and Menkes diseases, which result from genetic mutations affecting copper transport. Therefore, while copper is highly important for health, its industrial use must be controlled in such a way as to lessen the environmental and health impacts.

CHAPTER 4

Chemistry of Corrosion Inhibitors for Protecting Aluminium and its Alloys

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Abstract: Aluminium and its alloys are extensively utilized across aerospace, marine, automotive, and construction industries due to their exceptional strength-to-weight ratio, excellent electrical conductivity, and inherent resistance to corrosion. However, in harsh environments—particularly those containing chlorides or acidic media—these materials might experience localized corrosion, compromising their structural integrity and performance. This chapter presents a thorough overview of corrosion inhibitors used to safeguard aluminium and its alloys, concentrating on their chemical properties, categorization, and modes of action. Detailed discussions encompass the adsorption characteristics of inhibitors on metal surfaces, the influence of molecular structure and functional groups, as well as the use of electrochemical techniques like electrochemical impedance spectroscopy and potentiodynamic polarization for evaluating corrosion inhibition performance. The chapter also discusses current breakthroughs in green inhibitors produced from plant extracts, amino acids, and other natural sources, which provide more sustainable and ecologically friendly alternatives to traditional inhibitors. Temperature, concentration, pH, and synergistic effects are all investigated as important factors influencing inhibitory efficiency. This research intends to help with the rational design and selection of high-performance corrosion inhibitors for industrial applications, with an emphasis on environmentally responsible and cost-effective solutions.

Keywords: Aluminium alloys, Adsorption, Corrosion inhibition, Electrochemical techniques, Green inhibitors, Surface protection, Sustainable chemistry.

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INTRODUCTION

Structural and Functional Characteristics of Aluminium

Aluminium, formerly more expensive than gold due to the complexity of its mining, has developed into one of the most frequently used metals in modern industrial civilization. Aluminium's distinctive combination of properties—such as a high strength-to-weight ratio, low density, excellent electrical and thermal conductivity, and strong reflectivity—makes it highly suitable for diverse applications. These range from aerospace structures and automotive parts to electrical wiring, architectural designs, and food packaging materials [1 - 3].

Aluminium crystallises in a face-centered cubic (FCC) lattice and has great ductility and workability, allowing it to be easily formed into complicated forms [4]. Aluminium's natural resistance to corrosion primarily stems from the spontaneous formation of a thin, stable oxide layer on its surface. This passive film acts as a protective shield, effectively preventing further oxidation and deterioration of the underlying metal [5 - 7]. However, the electrochemical stability of this passive film varies depending on the context and can worsen in the presence of hostile circumstances such as excessive salinity, severe pH levels, and chloride ions. When the passive oxide layer is compromised, aluminium becomes vulnerable to localized corrosion, including pitting (Fig. **1**), intergranular corrosion, crevice corrosion, and stress corrosion cracking. These forms of attack can significantly degrade the structural integrity of the material over time [8, 9].

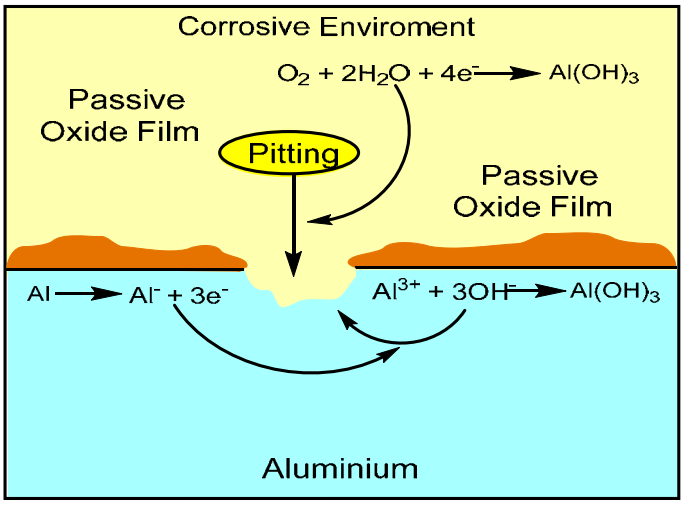

Fig. (1). Illustration of the mechanism of aluminium corrosion, showing how the naturally protective oxide layer initially forms on the metal surface, followed by its gradual breakdown under aggressive environmental conditions [8].

Furthermore, aluminium is rarely employed in structural applications in its pure state. Instead, it is widely alloyed with copper, magnesium, silicon, manganese, and zinc to increase mechanical strength and customize other useful properties. While these alloying additions greatly increase the usefulness of aluminium, they can also produce microstructural heterogeneities and galvanic couples that have a negative impact on corrosion behavior. The corrosion behavior of aluminium-based systems is substantially influenced by factors, such as alloying complexity, impurity levels, heat treatment history, surface quality, and residual stresses [10 - 12]. These factors underscore the importance of understanding not only the ambient conditions, but also the underlying metallurgical variables that govern corrosion in aluminium and its alloys [13].

The influence of alloy composition and microstructure is equally significant when considering the performance of corrosion inhibitors. Different alloying elements, such as copper, magnesium, and zinc, frequently inject secondary phases or intermetallic particles onto the metal surface, creating galvanic activity sites and altering inhibitor adsorption behavior. For example, copper-rich portions in high-strength alloys may increase localized attack, whereas magnesium-containing phases dissolve preferentially, altering the overall corrosion response. Grain size, precipitate dispersion, and dislocation density all influence how protective layers develop and maintain stability following exposure. Alloys with fine and homogenous microstructures give more consistent adsorption sites, whereas heterogeneous or coarse features might disrupt inhibitor layer continuity. Heat treatments and thermomechanical processes, which change phase morphology and residual stress states, also influence inhibitor effectiveness. For these reasons, modifying inhibitors to the unique chemistry and microstructural properties of an alloy is vital to offer lasting and reliable corrosion protection in severe applications [14, 15].

Essentiality and Ramifications of the Aluminium Industry

The prevalence of aluminium in modern life cannot be understated. Aluminium is a crucial facilitator of lightweight, energy-efficient, and recyclable solutions in a variety of high-impact industries. Aluminium is used in the transportation industry to create fuel-efficient cars and airplanes [16]. It encourages the construction of energy-saving buildings. It serves as the foundation for electrical power distribution networks. The material is also useful in the packaging business since it provides lightweight, corrosion-resistant, and infinitely recyclable containers that contribute to global sustainability goals [17, 18].

The aluminium sector is a significant contributor to worldwide economic progress, technical innovation, and environmental responsibility. However, the

CHAPTER 5

Role of Biomass Corrosion Inhibitors in Metal Corrosion Inhibition

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Abstract: Corrosion is one of the major problems faced in various environmental-related fields, causing environmental harm, safety issues, and large financial losses. Despite being efficient conventional corrosion inhibitors, synthetic compounds, such as chromates and phosphates, are hazardous and non-biodegradable, which is bad for the environment and human health. Biomass-based corrosion inhibitors (BCIs) are an excellent alternative that is both environmentally friendly and effective. Among the eco-friendly sources of BCIs are plant extracts, agricultural waste, and microbiological by-products. They create layers of defence by using bioactive substances like tannins, alkaloids, and flavonoids to prevent metal surfaces from corroding. These inhibitors offer inexpensive, biodegradable solutions while minimizing their environmental impact by adhering to green chemical principles. This chapter provides a detailed analysis of BCIs, including their origins, modes of operation, benefits, and limitations. Along with suggestions for improving scalability and efficiency, significant topics are covered, such as solubility issues, extraction inefficiencies, and performance in highly industrialized settings. Enhancing BCI performance has been highlighted as primarily reliant on computer modelling, the integration of nanomaterials, and green extraction techniques. The chapter emphasizes BCIs' potential for sustainable addressing of industrial corrosion, highlighting their role in encouraging environmental stewardship, cutting costs, and supporting the circular economy.

Keywords: Adsorption mechanisms, Bioactive compounds, Biodegradable inhibitors, Biomass-based corrosion inhibitors (BCIs), Corrosion, Eco-friendly inhibitors, Green chemistry, Plant extracts, Renewable resources, Sustainable corrosion protection.

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INTRODUCTION

One of the major worldwide problems is corrosion, causing metal degradation *via* chemical and electrochemical interactions with its surroundings [1 - 4]. In sectors including building, transportation, oil, gas, and marine engineering, it generates significant economic losses, safety risks, and environmental concerns. The oxidation and degradation of metal surfaces are caused by the interaction of metals with ambient elements, such as oxygen, moisture, acids, and salts. The effects of corrosion on the economy are profound, with billions of dollars spent annually on corrosion prevention and maintenance. In critical infrastructure, such as bridges, pipelines, and industrial machinery, corrosion may lead to structural failures, safety hazards, and an increase in operational costs [5]. In the marine and oil industries, where metals are exposed to highly corrosive environments, the consequences of corrosion are even more severe, leading to potential environmental disasters and loss of life [6, 7]. The use of corrosion inhibitors is among the most popular ways to prevent or slow down metal degradation. To slow down corrosion, conventional corrosion inhibitors like synthetic compounds, including chromates, phosphates, and nitrites, are extensively used. These inhibitors either create a protective layer on the metal surface or interact with the electrochemical sequence, causing corrosion. Nevertheless, the toxicity, great cost, and environmental impact of these synthetic inhibitors have motivated the search for eco-friendly substitutes that can effectively prevent corrosion without compromising the surroundings. Because of their environmentally friendly character, economy, and great efficiency in recent years, biomass-based corrosion inhibitors are attracting a lot of interest [8 - 12].

Due to their renewable character, biodegradability, and environmental compatibility, biomass-based corrosion inhibitors have become an interesting solution. These inhibitors come from natural sources, such as extracts from plants, agricultural waste, algae, and microbial byproducts, and have bioactive compounds that can reasonably slow down corrosion processes as shown in Fig. (**1**). Many studies have shown that compounds including tannins, alkaloids, polyphenols, saponins, and flavonoids present outstanding corrosion inhibition qualities, which provide a barrier against corrosive substances by adhering to the metal surface. The need for eco-friendly solutions consistent with green chemistry ideas drives the increasing curiosity in biomass-based inhibitors. Unlike synthetic inhibitors, which can be persistent in the environment and pose health hazards, biomass inhibitors break down organically and have less of an ecological effect. Many of these inhibitors are easily obtained and reasonably priced since they are derived from agricultural byproducts or plant materials. Plant-derived inhibitors have been investigated in several environments—including acidic, neutral, and saline conditions—by several research studies. Based on the data, at suitable

dosages, biomass-based inhibitors can offer either equivalent or even better protection against corrosion. Furthermore, it has been noted that the combined action of several plant compounds improves their inhibitory qualities, hence they offer a good substitute for traditional inhibitors. The function of biomass corrosion inhibitors in metal corrosion inhibition is given in this chapter in brief. It looks for their sources, chemical makeup, and ways of action, benefits, and drawbacks. Currently, developments and future viewpoints in this field will be explored to underline the possibilities of biomass inhibitors as environmentally friendly substitutes for corrosion prevention techniques. By means of this conversation, the chapter seeks to add to the increasing corpus of information on environmentally friendly corrosion control and its relevance in industrial uses. The main emphasis will be on realizing the possibilities of biomass-based inhibitors, investigating their several uses, and solving the obstacles required for their general acceptance in industrial environments.

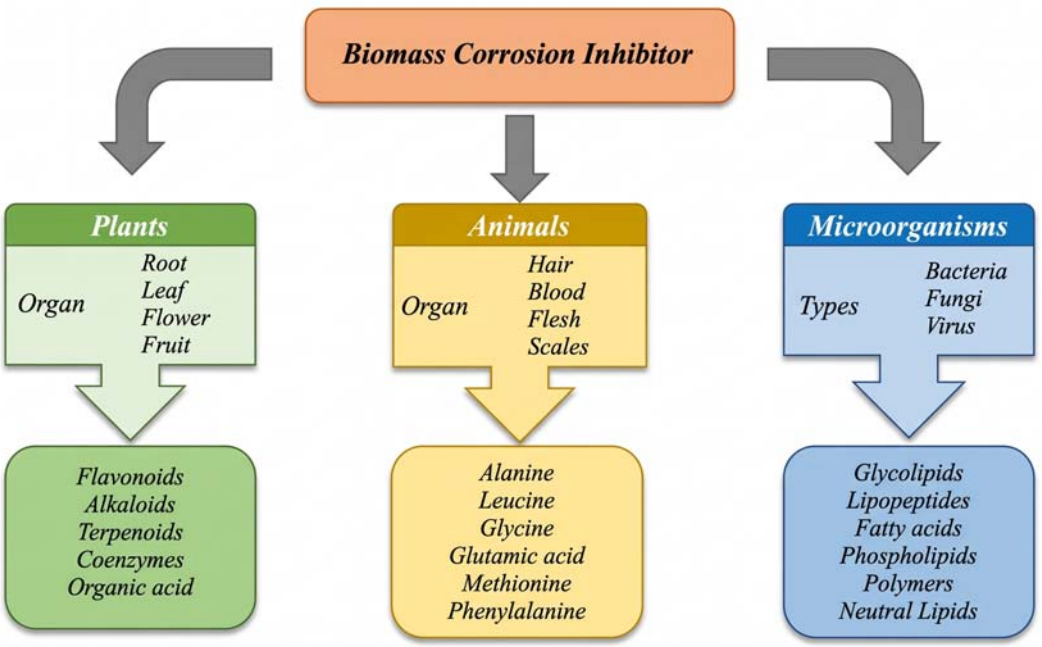

Fig. (1). Sources of biomass corrosion inhibitors—plant extracts, amino acid derivatives, and microbial biosurfactants (Reprint from [13]).

Importance of Corrosion Control in Various Industries

From oil and gas to marine, aerospace, and construction, corrosion affects many different sectors. Effective corrosion control is absolutely essential in these industries to guarantee infrastructure safety, lower maintenance costs, and extend

CHAPTER 6

Advancements in the Synthesis of Corrosion Inhibitors

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Abstract: The current chapter represents a comprehensive overview of recent developments in the field of chemical compounds with anti-corrosive properties. Among the potentially strong candidates, flavonoids have emerged due to their rich aromatic skeleton and presence of heteroatoms, which play a role in coordinating with metal surfaces. Synthetic methodologies such as aldol condensation, Friedel–Crafts acylation, Suzuki coupling, cyclization, and demethylation have been employed to achieve the highest yield of the products. Some hazardous chemicals such as toluene, DMSO, $AlCl_3$, and DIPE raise some environmental concerns, whereas implementing cyclodehydration in acetic and sulfuric acid results in a high yield with a shorter reaction. To accelerate the synthetic procedure, a regioselective Friedel–Crafts acylation operates in just two steps to provide the desired product. The anti-corrosive property in the reported products remains intact. There are more such reports with high yields of the products through single step reaction with effective anti-corrosive properties. Other than flavonoids, linseed oil, imidazolium ionic liquids, tung oil, and cashew nut shell liquid-based corrosion inhibitors have been mentioned in this chapter.

Keywords: Anti-corrosive property, Flavonoids, Friedel–Crafts acylation, Methodologies, Suzuki coupling.

INTRODUCTION

Corrosion is the degradation of a material due to a chemical reaction between the material and molecules in its environment. Corrosion represents a destructive phenomenon that affects the sustainability, functionality, and safety of metallic

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materials [1 - 4]. Common environmental corrosion agents include moisture, oxygen, and other corrosive substances. General corrosion-related issues have a significant impact, ranging from infrastructure degradation to machinery failure, resulting in substantial economic losses and environmental issues [5 - 7]. Metals that offer mechanical strength and cost-effectiveness can corrode to a non-usable state, especially under acidic and humid conditions, thereby reducing their lifespan. Naturally occurring corrosion mechanisms, such as (i) uniform corrosion, (ii) localized corrosion, and (iii) stress corrosion cracking, play a role in corroding metals, but there are different types of chemical corrosion, such as pitting, crevice, intragranular, and galvanic corrosion, which can be mitigated by certain methods [8 - 11]. To overcome these corrosion issues, several strategies have been developed, such as cathodic and anodic protection, protective coatings, and synthesis of corrosion inhibitors. An effective method to inhibit corrosion is to synthesize organic materials capable of forming protective layers on metals through adsorption, with the synthesis process being efficient and economical and following green chemistry principles. Some naturally found organic inhibitors have been mentioned in Fig. (**1**), such as caffeic acid (1), gallic acid (2), ferulic acid (3), chlorogenic acid (4), benzonitriles (5), and chrysin (6). These molecules exhibit strong adsorption tendencies on metal surfaces by forming protective coats that reduce corrosion rates. These compounds are widely explored for eco-friendly corrosion inhibition strategies [12 - 15]. As attention has shifted towards the development of eco-friendly and sustainable corrosion inhibitors, green inhibitors derived from plant extracts, amino acids, natural polymers, drugs, and especially ionic liquids and metal-organic frameworks, have emerged as the most effective candidates due to their biodegradability, low toxicity, and effectiveness at low concentrations [16 - 19]. Luteolin is a well-known naturally occurring nutritional flavonoid, and it has different types of biological activities, such as antioxidant, antiallergic, anti-inflammatory, antibacterial, antiviral, anti-Alzheimer's, antimutagenic, anti-angiogenesis, anti-chikungunya, anticancer, neuroprotective, and antiamnesic, and it acts as an anticorrosion agent [20 - 24]. Other than luteolin, this report includes PHU-based coaters derived from linseed oil, choline-based ionic liquids, Schiff bases, 8-hydroxyquinoline derivatives, benzoxazine precursors, non-isocyanate polyurethanes (NIPUs), and silicon-added cashew nut shell liquid derivatives [25 - 28].

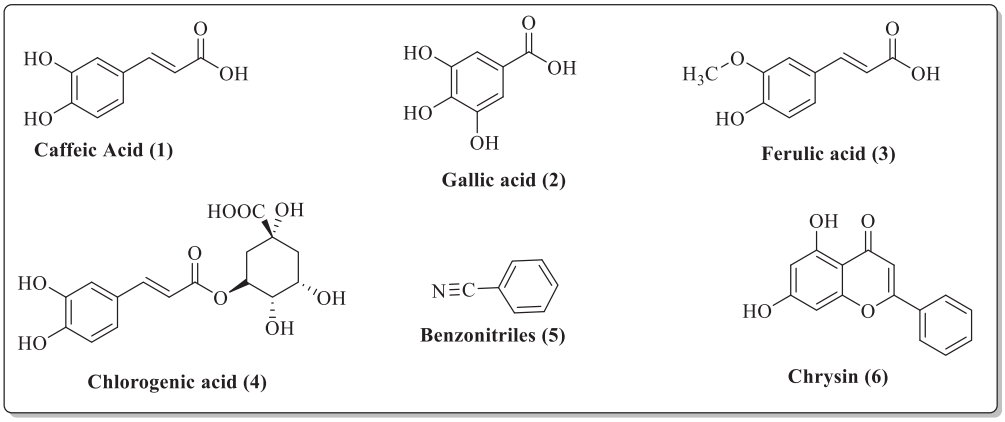
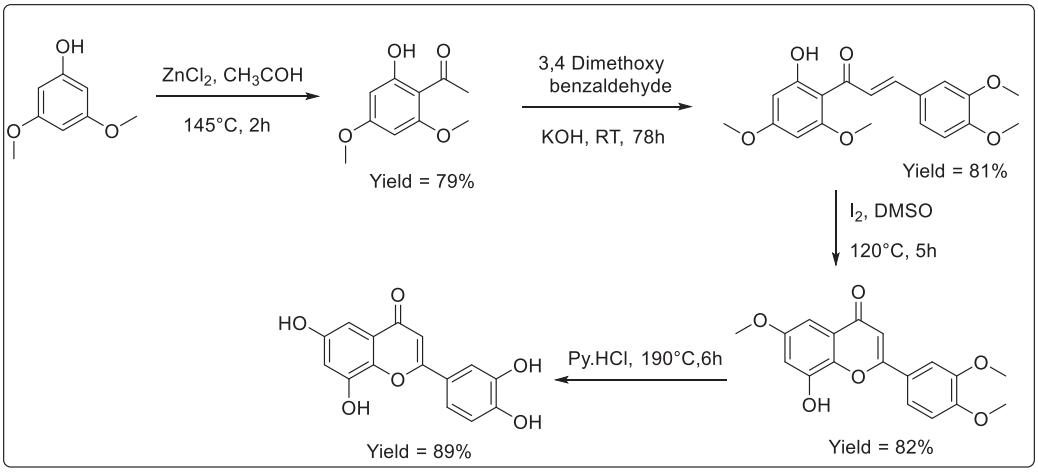


Fig. (1). Naturally occurring organic compounds with potential corrosion inhibitor properties.

SYNTHETIC APPROACHES TO PRODUCE ORGANIC PRODUCTS CONTAINING CORROSION INHIBITORY PROPERTIES



Scheme (1). Synthesis of novel anticorrosive flavonoids.

Qian Wang *et al*., reported the synthesis of dietary flavonoid luteolin in 2015 (Scheme **1**). In this synthesis, 4-steps were involved to generate the desired product luteolin under mild reaction conditions. In the first step, 3,5-dimethoxyphenol was treated with zinc chloride using CH_3COH to produce 2-hydroxy-4,6-dimethoxyacetophenone, which underwent aldol condensation with 3,4-dimethoxybenzaldehyde with the help of potassium hydroxide to generate chalcone in good yield. Chalcone was treated with iodine in DMSO to give 2-(3, 4-dimethoxyphenyl)-8-hydroxy-6-methoxy-4H-chromen-4-one, which underwent

CHAPTER 7

Role of Nanomaterials and Nanocomposites in Corrosion Inhibition

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Abstract: Corrosion remains a critical challenge in material science, affecting the longevity and structural integrity of metals across various industries. This chapter provides an overview of corrosion processes, their impact, and the need for effective corrosion inhibition strategies. Emphasis is placed on corrosion inhibitors, particularly the evolution from traditional chemical inhibitors to advanced nanomaterial-based systems. The unique physicochemical properties of nanomaterials, such as high surface area, reactivity, and tunable morphology, make them highly effective in enhancing corrosion resistance. This categorizes corrosion inhibitors into organic, inorganic, and green inhibitors, highlighting the limitations of conventional approaches, including environmental concerns and poor long-term performance. In contrast, nanomaterials, such as metal and metal oxide nanoparticles, quantum dots, and nanotubes, exhibit superior performance due to their ability to form uniform protective layers, promote barrier properties, and, in some cases, provide self-healing functionality when embedded in coating systems.

Furthermore, the chapter outlines the classification of nanomaterials based on composition, structure, and dimensionality. Synthesis techniques-including physical, chemical, and green routes-are discussed, emphasizing methods that promote dispersion stability and eco-friendliness. By integrating nanomaterials into corrosion protection systems, the potential for developing sustainable, efficient, and high-performance anti-corrosive solutions is significantly enhanced. This review serves as a foundational reference for future innovations in nanotechnology-based corrosion inhibition.

Keywords: Carbon nano tubes, Carbon nano-fibres, Ceramic nanoparticles, Corrosion inhibitors, Corrosion, Graphene, Lipid nanoparticles, Nano particles, Nanocomposites, Nanomaterials, Quantum dots.

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INTRODUCTION

Corrosion is a complex electrochemical process that results in the gradual degradation of materials, particularly metals, due to their interaction with environmental elements such as oxygen, moisture, and industrial chemicals [1]. In both academic and industrial contexts, corrosion poses significant challenges related to safety, operational efficiency, and economic impact [2]. According to a comprehensive study by the National Association of Corrosion Engineers (NACE), the global cost of corrosion is estimated to exceed $2.5 trillion annually, representing approximately 3-4% of the global gross domestic product (GDP) (NACE International, 2016) [3]. This economic burden affects a wide range of industries, including oil and gas, transportation, infrastructure, and water systems, where corrosion leads to structural failures, equipment damage, environmental contamination, and increased maintenance costs [4]. As a result, industries prioritize corrosion prevention through the use of protective coatings, corrosion-resistant alloys, cathodic protection, and continuous monitoring systems to extend the lifespan of assets and ensure safety.

Redox reactions occur at the external interface because corrosion processes are naturally electrochemical in nature [5]. Corrosion mechanisms can vary based on material type, the type of corrosive environment, and the presence of additional substances. Rusting, *i.e.*, a redox reaction, occurs at the material interface because corrosion processes are naturally electrochemical in nature [6], as shown in Fig. (**1**). Corrosion mechanisms can vary based on material type, the type of corrosive environment, and the presence of additional substances. Rusting, pitting, cracking, and other types of damage may arise from the development of these reactions [7]. This increases the risk of equipment breakdown, the failure of certain methods, and safety risks. Understanding these mechanisms is crucial for preventing and minimizing corrosion, maintaining material integrity, and extending service life, thus enhancing overall performance [8]. Regarding corrosive environments, corrosion can be grouped as dry or wet [9]. Pitting, cracking, and other types of damage may arise from the development of these reactions, affecting overall performance.

Corrosion Inhibitors

Corrosion inhibitors are chemical compounds that are either admixed into concrete or applied to its surface to mitigate the deterioration of embedded steel reinforcement, primarily caused by chloride ingress and carbonation [10].

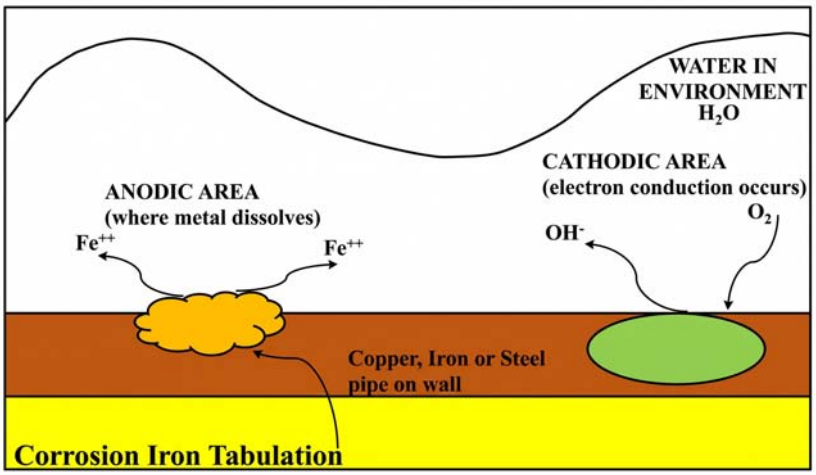

Fig. (1). Corrosion process illustrating oxidation at the anodic site, reduction at the cathodic site, and rust formation as a result of electrochemical redox reactions.

These inhibitors function by either enhancing the passivity of the steel surface or interfering with the electrochemical processes responsible for corrosion. Anodic inhibitors, such as calcium nitrite, oxidize ferrous ions and promote the formation of a stable passive oxide film, thereby delaying the initiation of corrosion [11, 12]. Cathodic inhibitors, like amino alcohols, suppress the oxygen reduction reaction at cathodic sites, while mixed inhibitors combine both mechanisms to offer comprehensive protection [13]. Recent advancements have introduced nanomaterials as potential corrosion inhibitors, offering multifunctional benefits, such as reduced permeability, chloride ion binding, and smart-release capabilities. The effectiveness of corrosion inhibitors depends on several factors, including the type of cement, water-cement ratio, environmental exposure, and the compatibility of admixtures.

Broad Classification of Corrosion Inhibitors

A. Based on the Mechanism of Action

1. Anodic Inhibitors

- **Function:** Prevent corrosion by forming a passive film at the anodic site (where metal dissolves).
- **Examples:** Calcium Nitrite ($Ca(NO_2)_2$)
- **Key Features:** React with ferrous ions to form ferric oxide, raise the chloride threshold level, and are often used as an admixture during mixing [10, 14].

CHAPTER 8

Applications of Corrosion Inhibitors

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Abstract: Corrosion inhibitors play a crucial role in safeguarding metallic infrastructure across various industries, including electronics, petroleum, military, and cooling systems. This chapter provides a comprehensive overview of their applications, traditional methodologies, and recent advancements. These inhibitors function by interrupting the electrochemical processes of corrosion through mechanisms, such as film formation, adsorption, and neutralization. A growing emphasis on sustainability has prompted the development of green inhibitors derived from natural and biodegradable sources. Incorporating advanced delivery systems, such as encapsulation, has resulted in multifunctional solutions. In the electronics sector, volatile inhibitors and protective coatings are utilized to safeguard components. Within the petroleum industry, inhibitors are employed to mitigate corrosion in upstream operations, pipelines, and refineries. The natural gas sector applies these inhibitors to manage top-of-the-line corrosion. For military applications, inhibitors are employed to protect naval vessels, aircraft, and field equipment. Coatings enhanced with inhibitors offer properties, such as self-healing and smart-release functionalities. Cooling systems require formulations that address complex challenges specific to the industry. Looking forward, the focus of corrosion inhibition is expected to be on customization, novel materials, and the use of computational design to achieve high-performance and environmentally benign solutions.

Keywords: Cooling water systems, Corrosion inhibitors, Electronics industry, Military applications, Natural gas industry, Petroleum industry, Volatile corrosion inhibitors (VCI).

INTRODUCTION

Corrosion inhibitors represent one of the most practical and economically viable methods for ameliorating metal deterioration across various industries. These specialized chemical compounds, even when introduced in minimal concentrations into corrosive environments, can markedly diminish corrosion

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rates and prolong the operational lifespan of essential infrastructure. This chapter investigates the diverse applications of corrosion inhibitors across six principal sectors, scrutinizing both traditional methodologies and pioneering advancements that influence corrosion protection strategies. The efficacy of corrosion inhibitors stems from their capacity to disrupt the electrochemical processes responsible for corrosion. They generally operate *via* mechanisms, such as film formation on metal surfaces, adsorption that obstructs active corrosion sites, neutralization of corrosive species, and modification of the electrical potential at the metal-solution interface. As delineated throughout this chapter, the selection of suitable inhibitors is contingent upon numerous factors, including the specific metal substrate, environmental conditions, operational parameters, and environmental considerations.

In recent years, significant advances have been made in corrosion inhibitor technology. The traditional focus on performance has expanded to incorporate environmental sustainability, resulting in the development of "green" inhibitors derived from natural sources, such as plants. Moreover, nanotechnology has enabled the creation of more effective inhibitor delivery systems, and computational modeling has enhanced our understanding of the inhibition mechanisms at the molecular level.

This chapter presents a comprehensive overview of the use of corrosion inhibitors in various industrial applications, highlighting established practices and emerging trends that promise to shape the future of corrosion protection.

ELECTRONICS INDUSTRY

Protecting Sensitive Components

The electronics industry represents one of the most challenging areas for corrosion protection research. Modern electronic devices contain numerous metallic components, from copper traces on printed circuit boards (PCBs) to gold-plated connectors and aluminum heat sinks, all of which can be vulnerable to corrosive attacks. Even microscopic levels of corrosion can lead to catastrophic failures in electronic systems, making effective inhibition strategies essential for their long-term reliability.

Corrosion in electronics is particularly insidious because it can occur through multiple mechanisms. Atmospheric corrosion from humid environments, galvanic corrosion at the junctions of dissimilar metals, and electrolytic corrosion in the presence of condensed moisture are common concerns. The trend toward miniaturization in electronics further complicates protection strategies because traditional coating approaches may interfere with electrical functions or heat

dissipation. Corrosion inhibitors designed for electronics must satisfy several specialized requirements.

- They must form extremely thin protective films that do not impede electrical conductivity.
- They cannot leave residues that could interfere with signal transmission.
- They must remain effective at very low concentrations.
- They should provide long-term protection without requiring reapplication.

Volatile Corrosion Inhibitors (VCI)

Volatile Corrosion Inhibitors (VCIs) have emerged as crucial technologies to protect electronic components. These inhibitors function by slowly releasing active compounds that vaporize and condense on metal surfaces, thereby forming a protective molecular layer. As noted by Valdez *et al*., [1] and Cheng *et al*., [2], VCIs can be applied in various forms, including powders, sachets, or impregnated papers, creating a protective atmosphere around electronic components. The key advantages of VCIs in electronics include the following:

- Their ability to reach inaccessible areas through vapor-phase transport.
- Formation of self-healing protective films that can reform if damaged.
- The capacity to protect multiple metal types simultaneously.
- Compatibility with enclosed environments, such as sealed electronic packages.

Electronic manufacturers commonly incorporate VCI technology into the packaging of sensitive components, particularly products that can be exposed to varying climatic conditions during shipping and storage. These inhibitors provide a first line of defense against atmospheric corrosion before devices are used.

Conformal Coatings with Embedded Inhibitors

Conformal coatings represent another critical application of corrosion inhibitors in the electronics industry. These thin polymeric films are applied to circuit boards to protect them from moisture, dust, and chemical contaminants. Modern conformal coatings frequently incorporate corrosion inhibitors to enhance their protective ability.

Lee *et al*., [3] highlight the importance of fluorine-based coatings that incorporate corrosion inhibitors to protect outdoor electronics, particularly in environments where sulfur-containing gases are prevalent. These specialized coatings can meet rigorous industry standards, such as the ANSI/ISA G3 corrosion test, demonstrating their effectiveness in harsh environments.

SUBJECT INDEX

A

Acidic conditions 59, 74, 93, 97, 102, 131, 137
Acidic environments 13, 14, 57, 73, 77, 94, 100, 122, 135, 137, 197
Acidic solutions 50, 73, 79, 95, 97, 121, 122, 218
Acids 19, 21, 46, 50, 56, 62, 64, 118, 126, 127, 134
Adhering 20, 40, 104, 117, 118, 122, 130, 145
Adsorption 12, 13, 17, 32, 33, 46, 51, 71, 77, 79, 80, 94, 126, 129, 130, 132, 133, 147, 199
  film-forming 126, 130, 147
  gaseous 51
  inhibitor's 94
  molecular 46, 51
Adsorption mechanisms 12, 79, 96, 106, 117, 130, 133
  chemical 130
  physical 96, 106
Alkaloids 13, 21, 56, 60, 62, 63, 65, 66, 117, 118, 125, 126, 128, 133, 134, 138, 143, 144
Alloys 56, 60, 62, 63, 65, 66, 134
  aluminium-bronze 65
  aluminum 134
  aluminum bronze 63
  copper-based 56, 60, 62, 63, 65, 66
Aluminium alloys 93, 94, 95, 97, 98, 99, 100, 104, 105, 106, 107, 196, 197
Amines 10, 50, 122, 142
Amino acids 13, 46, 50, 88, 92, 125, 128, 133, 135, 231, 232
  sulfur-containing 135
Anode 20, 35, 70, 94
Anodic and cathodic reactions 10, 61, 69, 70, 71, 73, 103, 138
Anodic inhibitors 9, 20, 35, 36, 37, 38, 51, 72, 98, 181, 227
  traditional 37
Anti-corrosive properties 155, 163, 164, 165, 168
Atomic force microscopy (AFM) 17, 71, 92, 93, 96, 140, 146

B

Bacteria 63, 125, 130, 134, 135, 145, 185, 194
  sulfate-reducing 130, 185
Based corrosion inhibitors (BCIS) 117, 118, 125, 126, 130, 133, 136, 140, 144, 145, 147
Benzotriazoles 35, 42, 50, 51, 67, 70, 71, 199, 228
Biodegradability 14, 48, 118, 125, 138, 142, 145, 156, 220, 231
Bonds 41, 42, 57
  double 57

C

Carbon nanotubes (CNTS) 22, 24, 183, 189, 190, 193, 195, 196, 197, 198, 199, 232
Carbon steel 6, 63, 127, 134, 135, 136, 140, 141, 225, 228, 229
Carbonates 35, 38, 43, 44, 95, 158, 188
  calcium 38, 44
  potassium 158
  sodium 95
Cathodic 16, 20, 37, 38, 40, 50, 51, 69, 73, 101, 135
Cathodic inhibitors 9, 12, 20, 37, 38, 39, 51, 181, 182, 228
Cathodic protection 32, 33, 65, 91, 121, 180, 221
Cathodic reactions 10, 12, 20, 37, 38, 43, 51, 69, 70, 71, 73
Cathodic sites 10, 60, 129, 181, 182, 225, 228
Chitosan 95, 96, 105, 108, 137, 142, 232

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Chloride ions 12, 59, 60, 62, 89, 122, 130, 197
Chlorides 56, 67, 137, 195, 225
Coatings 8, 9, 25, 26, 38, 67, 96, 120, 169, 196, 203, 204, 223, 224, 225, 226
  anticorrosive 169
Compounds 13, 20, 33, 35, 56, 57, 70, 71, 72, 74, 75, 80, 94, 124, 125, 215, 216, 223
  anti-corrosive 70
  heterocyclic 13, 20, 94
Cooling systems 8, 23, 50, 51, 122, 212, 221, 228, 229, 230, 231
Copper alloys 56, 61, 62, 63, 65, 67, 73, 76
Copper surface 58, 62, 65, 69, 70, 71, 74, 77, 79, 80, 215
Corrosion 1, 2, 3, 7, 25, 32, 35, 56, 59, 61, 64, 65, 67, 71, 73, 118, 120, 121, 123, 180, 185, 201, 222, 225
  accelerated 71, 222
  alloy 123
  anti-bacterial 185
  chloride-induced 64
Corrosion control 3, 26, 33, 48, 119, 120, 147
  efficient 147
  friendly 119
Corrosion inhibition 41, 179
  nanotechnology-based 179
  organic 41
Corrosion inhibition efficiency 48, 49, 56, 80, 94, 169, 174
  high 49
  highest 94
Corrosion prevention 23, 118, 120, 121, 125, 126, 180
  complicated 121
  continuous 23
  industries prioritize 180
  maintaining effective 125
Corrosion processes 14, 16, 59, 75, 122, 145, 179, 180, 181, 221, 225, 228
  inhibiting 122
Corrosion protection 67, 73, 122, 123, 142, 145, 195, 197, 213, 215, 218, 220, 223, 224, 225
  electronic 215
  natural-gas 220
Corrosion rate 15, 24, 39, 43, 46, 64, 68, 69, 70, 71, 73, 78, 96, 97, 121, 124, 127, 130, 197, 200
  average 15, 64
  decreased 46
  high 24, 39
  lower 43, 121
Corrosion resistance 46, 58, 59, 61, 64, 65, 67, 95, 99, 100, 101, 120, 121, 122, 126, 224
  exceptional 224
  good 58
  improved 100
  maximum 61
Corrosive agents 62, 66, 67, 121, 122, 125, 126, 127, 130, 134, 197, 199
  aggressive 127
  strong 126
Corrosive environments 23, 25, 118, 121, 122, 123, 127, 130, 145, 147, 180, 212, 216

D

Degradation 6, 32, 35, 56, 62, 63, 69, 118, 155, 195, 197, 198, 224, 232
  corrosive 56
  environmental 197, 224
  microbial 232
Delivery systems 22, 24, 26, 215
  designing corrosion inhibitor 24
  nanostructured 24
Derivatives 71, 73, 74, 76, 125, 197, 232
  agro-waste 125
  starch 232
Dimensions 58, 95, 188, 190, 191, 201
  socio-economic 58
Dissolution 51, 57, 59, 91, 135, 202

reducing metal ion 135

E

Efficiency 21, 22, 42, 48, 50, 81, 103, 105, 106, 134, 135, 136, 138, 139, 143
Electrochemical impedance spectroscopy (EIS) 16, 67, 74, 76, 77, 79, 80, 88, 92, 93, 97, 101, 103, 135, 140, 142
Electrochemical processes 4, 6, 19, 49, 60, 99, 122, 180, 181, 212, 213
complex 180
fundamental 49
Electrochemical reactions 2, 6, 11, 20, 122, 137
Electrolytes 6, 43, 73, 97, 137, 203, 221
ideal 221
Electronics 51, 184, 186, 189, 195, 212, 213, 214, 215, 231, 232
flexible 189
outdoor 214
specialized 232
Environmental conditions 15, 19, 26, 62, 66, 126, 127, 136, 143, 213, 222
Environments 13, 18, 60, 66, 119, 126, 135, 198
chloride-rich 13, 60, 198
industrial 18, 66, 119, 126, 135
Extract 46, 47, 48, 93, 94, 98, 100, 101, 127, 129, 136, 137, 141, 201
banana peel 127, 136, 137
biopolymer-derived 136
leaf 201
Extraction 48, 103, 126, 143, 145, 146

F

Film formation 10, 13, 16, 36, 137, 138, 142, 146, 199, 212, 213
passive 10, 36
protective 13, 137, 142, 146
stable 138
Flavonoids 117, 118, 125, 126, 127, 130, 131, 133, 136, 143, 144, 155, 159, 160, 202
Formulations 38, 39, 123, 124, 144, 145, 212, 224, 229, 230, 232
sustainable 145
Functional groups 10, 38, 40, 41, 42, 96, 98, 127, 128, 129, 132, 133, 135, 137

G

Gas 23, 50, 118, 119, 123, 126, 139, 144, 180, 214, 217, 220
acid 220
sulfur-containing 214
Green corrosion inhibitors (GCIS) 2, 4, 13, 14, 46, 48, 51, 77, 92, 105, 135, 215, 220
Green inhibitors 1, 12, 13, 14, 21, 46, 47, 48, 88, 92, 199, 212, 213, 215
alkaloid-based 13
plant-derived 12
Group 75, 105, 127, 134, 135, 142, 219
aldehyde 105
carboxylate 142
electron-attracting 75
electron-releasing 75

H

HCl 46, 71, 72, 73, 94, 95, 100, 102, 103, 107, 136, 137, 141, 142, 159
Heteroatoms 10, 12, 15, 80, 81, 92, 96, 100, 102, 128, 129, 132, 135
Hybrid inhibitors 9, 10, 11, 13, 38, 39, 40, 51, 137
Hydrochloric acid 95, 97, 100, 102, 123, 137

I

Imidazole 20, 67, 73, 74, 76, 231
Industrial applications 21, 48, 63, 68, 88, 124, 213, 226
Inhibition 37, 41, 42, 47, 48, 51, 76, 77, 79, 80, 127, 129
effective 48
Inhibition efficiency 15, 16, 75, 77, 78, 79, 94, 95, 97, 99, 104, 106, 136, 137, 141
Inhibition mechanisms 39, 76, 79, 80, 94, 142, 146, 213
Inhibitor concentration 94, 95, 104, 136, 217
Inhibitor molecules 10, 17, 41, 78, 79, 122, 126, 127, 128, 129, 136, 137
Inhibitors 34, 118, 119, 126, 132, 133, 135, 140
acid-based 135
amine-based 34
biomass-based 118, 119, 126, 132, 133, 140
Innovations 2, 26, 90, 179, 204, 218, 221, 226

significant 226
technical 90
Inorganic inhibitors 9, 10, 42, 43, 44, 51, 67, 92, 122
Ions 19, 37, 45, 57, 91, 126, 127, 130, 136, 137, 187, 195, 225
  corrosion-inhibiting 225
  corrosive 127, 136, 137
Iron 44, 45, 46, 47, 60, 120, 122, 183, 186

L

Limitations 14, 22, 70, 91, 117, 123, 145, 179, 227
Linseed oil 155, 156, 162, 163, 172, 173
  carbonated 162, 163

M

Marine 23, 63, 65, 68, 88, 91, 118, 119, 120, 123, 135, 139
  corrosive 135
Mechanisms 11, 13, 14, 23, 24, 25, 61, 126, 127, 180, 181, 182, 200, 212, 213, 215, 225
  electrochemical 200
  self-healing 215
Medium 19, 33, 50, 73, 75, 96, 97, 100, 126, 130, 136, 137, 196
  acidic 100, 196
  corrosive 19, 33, 73, 97, 126, 130, 136, 137
  nitric acid 75
Metal surfaces 9, 10, 11, 13, 16, 17, 20, 22, 23, 24, 25, 75, 118, 122, 125, 126, 127, 128, 130, 135
Metallic surface 40, 41, 43, 46, 49, 59, 94, 129, 131
Metals 1, 2, 6, 19, 22, 23, 24, 32, 33, 35, 38, 42, 57, 61, 91, 120, 121, 122, 126, 128, 130, 203
  corrosion-resistant 91
  weld 61
Molecular structures 11, 15, 42, 49, 71, 77, 81, 88, 95, 96, 133
Molecules 12, 13, 49, 126, 136, 142, 143, 155, 156, 162, 164, 166, 169, 193, 199
  anti-corrosive 162, 169
  anti-corrosive coater 164
  base-derived 4-nitrocinnamaldehyde 164
  extract bioactive 126, 143

N

NaCl solution 39, 60, 66, 69, 71, 75, 98, 99, 101, 105, 186
Nanoparticles 11, 13, 14, 22, 24, 182, 184, 185, 186, 190, 191, 192, 193, 194, 196, 201, 202
  crystalline 194
  heavy metal 192
  inorganic 11, 185
  metallic 190
Nanotechnology 11, 14, 22, 24, 109, 196, 204, 213, 232
Nitrogen 17, 20, 62, 67, 80, 81, 92, 94, 100, 128, 129, 135, 137

O

Organic compounds 12, 40, 56, 70, 81, 126, 135, 157
  occurring 157
  sulfur-containing 135
Organic corrosion inhibitors (OCI) 38, 40, 41, 43, 44, 70, 129, 133, 182
Organic inhibitors 10, 13, 20, 21, 39, 40, 41, 42, 43, 122, 123, 124, 125, 182, 199
  commercial 182
  costly 21
Oxidation 36, 50, 57, 60, 62, 67, 89, 118, 181, 195, 202
Oxide layer 6, 20, 23, 39, 50, 56, 59, 89, 91, 121, 122, 195
  cerium 39
  dense 122

passive 50, 89, 91
protective 6, 23, 56, 89, 91, 121, 195
Oxides 37, 58, 60, 65, 74, 81, 99, 185, 188

P

Passivation 1, 9, 61, 65, 91, 200
electrochemical 200
Phosphates 36, 43, 44, 45, 46, 50, 67, 117, 118, 122, 123, 231
zinc iron 45
Physical adsorption 10, 41, 126, 127, 128, 130, 147, 164
Pipelines 3, 7, 8, 23, 25, 50, 51, 118, 120, 121, 212, 217, 219
gas transportation 3
Pitting 1, 2, 6, 7, 13, 16, 19, 36, 89, 121, 124, 180
localized 19
Plant extracts 46, 92, 94, 117, 119, 124, 125, 126, 127, 142, 144, 147, 215, 218, 220
Plants 39, 118, 122, 125, 127, 128, 143, 144, 145, 202, 226, 232
water treatment 122
Polymers 3, 23, 56, 92, 120, 190, 197, 199
Potentiodynamic polarization 16, 67, 74, 79, 80, 88, 92, 97, 103, 140
Protection 14, 15, 20, 22, 42, 43, 59, 60, 105, 106, 169, 198, 218, 219, 220, 222, 223, 225, 230
aluminum 222
electrochemical 198
environmental 169
Protective coatings 3, 8, 25, 38, 91, 197, 200, 212, 221, 222, 223
Protective films 12, 14, 58, 59, 74, 77, 95, 101, 103, 129, 130, 199, 201, 217, 219

R

Rate 21, 23, 24, 25, 35, 37, 61, 62, 64, 69, 70, 71, 73, 77, 80, 230
cathodic reaction 37, 70
initial efficiency 21
metal's dissolution 23
scale inhibition 230
Reactions 43, 45, 57, 59, 160, 161, 162, 164, 165, 166, 167, 168, 169, 173, 180
Reduction 4, 38, 39, 61, 74, 93, 103, 108, 139, 181, 202

S

Schiff bases 13, 42, 50, 122, 156, 164, 172
4-nitrocinnamaldehyde-based 164
nitrocinnamaldehyde-based 172
Seawater 59, 60, 63, 64, 95, 120, 130, 221, 226
sulfide-polluted 64
Sectors 7, 19, 58, 59, 118, 119, 120, 125, 126, 139, 203, 212, 213, 216, 218
industrial 19, 203
natural gas 212
petroleum 218
Solvents 48, 143, 145, 160
organic 143, 145
petroleum-based 145
Steel 35, 36, 41, 46, 120, 129, 130, 135, 140, 196, 199, 223, 226
embedded 120
safeguard 223
structural 226
Steel surface 24, 122, 137, 140, 141, 142, 164, 181, 182, 195, 220, 222
low-carbon 122
mild 164
Stress corrosion cracking (SCC) 1, 2, 7, 61, 62, 89, 124, 156
Sustainability 2, 4, 13, 19, 123, 125, 139, 143, 144, 147, 155, 212, 213, 220, 221
environmental 2, 213, 220
industrial 139
Synthesis 81, 145, 146, 157, 158, 159, 160, 161, 162, 164, 166, 167, 168, 171, 174, 193
graphene 193
Synthetic inhibitors 18, 21, 26, 46, 48, 118, 123, 124, 126, 134, 142, 145, 220, 229
high-performance 21
replacing 134, 145
traditional 26, 220
Systems 7, 23, 24, 25, 45, 48, 90, 125, 179, 220, 223, 224, 225, 227, 230
advanced nanomaterial-based 179
aluminium-based 90
amine 220
aromatic 125

T

Tannins 117, 118, 125, 126, 127, 130, 131, 133, 136, 143, 147, 202
Temperature 35, 38, 39, 61, 62, 80, 81, 93, 94, 95, 97, 103, 107, 108, 122, 123, 136, 137, 141, 164, 194, 216, 219, 220
  ambient 97, 103, 107
  elevated 35, 81, 103, 137, 194, 219, 220
  extreme 123, 216
Toxicity 21, 24, 44, 51, 67, 72, 92, 118, 123, 138, 147, 172, 173, 191, 196, 198, 231
  environmental 92, 138, 147, 196

W

Waste 32, 48, 139, 141, 232
  inorganic 232
  olive leaf 141
Weight loss (WL) 15, 70, 71, 73, 76, 77, 78, 80, 94, 95, 96, 100, 101, 102

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