NANOTECHNOLOGY FOR WASTEWATER TREATMENT

Editor:
Anjaneyulu Bendi

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Nanotechnology for Wastewater Treatment

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CONTENTS

FOREWORD i

PREFACE ii

LIST OF CONTRIBUTORS iv

CHAPTER 1 ROLE OF NANOTECHNOLOGY IN WASTEWATER TREATMENT 1
Versha and *Ravi Kumar Rana*
INTRODUCTION 1
The Elimination Effectiveness 2
The Regeneration and the Possibility of Reuse 2
A Catalytic Activity 2
The Adsorption Capacity 2
Enhanced Pollutants Elimination for Reusing Wastewater 3
Better Brackish Water and Seawater Desalination 3
Thin-film Nanocomposite (TFN) 3
Photothermal Nanomaterials 3
Nanocoating that Prevents Fouling 3
Energy-Saving Water Treatment Methods 3
APPLICATION OF NANOTECHNOLOGY IN WASTEWATER TREATMENT 4
Conventional Methods for Waste Water Treatment and their Limitations 4
Coagulation 4
Flocculation 5
Adsorption 6
Precipitation 6
Ion Exchange 7
Membrane Filtration 8
Electrochemical Treatment 8
NANOTECHNOLOGIES FOR WASTEWATER TREATMENT 9
Nanofiltration 9
Zero-Valent Metal Nanoparticles 10
Metal Oxides Nanoparticles 11
Carbon Nanotubes 12
Graphene-based Nanoparticles 13
Carbonaceous Nanoparticles 14
Nanocomposites 15
Types of Nanocomposites 15
Ceramic Matrix Nanocomposites 15
Metal Matrix Nanocomposites 16
Polymer Matrix Nanocomposite 16
Nano Sorbents 16
Carbon Nano Sorbents 17
Biosorbents 17
Nanofilters 18
Photocatalysis 19
Zeolites 21
CONCLUSION 22
LIST OF ABBREVIATIONS 22
ACKNOWLEDGEMENTS 23
REFERENCES 23

CHAPTER 2 CHEMISTRY OF ZERO-VALENT METAL NANOPARTICLES IN WASTEWATER TREATMENT 31
Minakshi, Prabhjot Kaur, Neera Raghav and *Rashmi Pundeer*
INTRODUCTION 31
Reactivity 32
Magnetic Properties 32
Redox Potential 32
Surface Modification 32
Synthesis Techniques 32
REDUCTION MECHANISM 33
ZERO-VALENT IRON NANOPARTICLES IN DYE DEGRADATION 34
Types of Dyes 35
Azo Dyes 35
Anthraquinone Dyes 36
Reactive Dyes 36
Research Methodology of Dye Degradation 36
ZERO VALENT IRON NANOPARTICLES IN THE TREATMENT OF INORGANIC POLLUTANTS FROM WASTEWATER 47
Treatment of Heavy Metals 47
Treatments of Inorganic Anions 58
CONCLUSION 63
LIST OF ABBREVIATIONS 63
ACKNOWLEDGEMENTS 65
REFERENCES 65

CHAPTER 3 METAL OXIDES NANOPARTICLES IN WASTEWATER TREATMENT 70
Taruna, Rajni and *Lakhwinder Singh*
INTRODUCTION 70
CHEMISTRY OF METAL OXIDES FOR THE REMOVAL OF HEAVY METALS 71
CHEMISTRY OF METAL OXIDES FOR THE REMOVAL OF DYES 77
ENVIRONMENTAL AND HUMAN HEALTH IMPLICATIONS 87
CONCLUSION 88
LIST OF ABBREVIATIONS 88
ACKNOWLEDGEMENTS 88
REFERENCES 89

CHAPTER 4 CARBON NANOTUBES IN WASTEWATER TREATMENT 93
Shubhika Goyal, Vishaka Chauhan, Chinmay Mittal and *Allu Udayasri*
INTRODUCTION 93
CHEMISTRY OF CARBON NANOTUBE COMPOUNDS FOR THE ADSORPTION OF POLLUTANTS PRESENT IN WASTEWATER BODIES 96
EFFECTS OF CARBON NANOTUBES ON THE ENVIRONMENT 110
CONCLUSION 111
LIST OF ABBREVIATIONS 111
ACKNOWLEDGEMENTS 112
REFERENCES 112

CHAPTER 5 GRAPHENE-BASED NANOCOMPOSITES IN WASTEWATER TREATMENT 117
Anirudh Singh Bhathiwal and *Anjaneyulu Bendi*
INTRODUCTION 117
DEGRADATION OF ORGANIC DYES USING GRAPHENE AND ITS DERIVATIVES 118
REMOVAL OF HEAVY METALS USING GRAPHENE AND ITS DERIVATIVES 124

CONCLUSION ... 132
LIST OF ABBREVIATIONS ... 132
ACKNOWLEDGEMENTS ... 133
REFERENCES ... 133

CHAPTER 6 CARBONACEOUS NANOPARTICLES IN WASTEWATER TREATMENT ... 137
Aditi Tiwari, M. Radha Sirija and *G. B. Dharma Rao*
INTRODUCTION ... 137
ROLE OF FULLERENES, NANODIAMONDS, AND CARBON QUANTUM DOTS IN WASTEWATER TREATMENT ... 138
NANODIAMONDS, QUANTUM DOTS, AND FULLERENES FOR WASTEWATER TREATMENT ... 140
Fullerenes-based Nanophotocatalysts ... 140
QUANTUM DOTS-BASED NANOPHOTOCATALYSTS ... 147
CONCLUSION ... 150
LIST OF ABBREVIATIONS ... 151
ACKNOWLEDGEMENTS ... 151
REFERENCES ... 151

CHAPTER 7 NANOCOMPOSITES IN WASTEWATER TREATMENT ... 155
G. B. Dharma Rao, Anirudh Singh Bhathiwal, Chinmay Mittal and *Vishaka Chauhan*
INTRODUCTION ... 155
REMOVAL OF HEAVY METALS FROM WASTEWATER ... 156
REMOVAL OF ORGANIC DYES FROM WASTEWATER ... 161
CONCLUSION ... 175
LIST OF ABBREVIATIONS ... 175
ACKNOWLEDGEMENTS ... 176
REFERENCES ... 176

CHAPTER 8 ROLE OF NANOSORBENTS IN WASTEWATER TREATMENT ... 180
Roopa Rani, Jaya Tuteja, Akanshya Mishra, Jasaswini Tripathy and *Arpit Sand*
INTRODUCTION ... 180
Water and its Contaminants ... 181
METHODOLOGIES USED FOR WASTEWATER TREATMENT ... 182
Direct Membrane Filtration ... 182
Coagulation / Flocculation ... 183
Advanced Oxidation ... 184
Biological Treatment ... 184
Adsorption ... 185
THE FUNCTION OF NANOPARTICLES IN THE ADSORPTION METHOD FOR WASTEWATER TREATMENT ... 186
TYPES OF NANOSORBENTS ... 186
Activated Carbon ... 187
Metal Oxide-based Nanosorbents ... 188
Titanium Oxide NP ... 189
Zinc Oxide NP ... 189
Copper Oxide NP ... 189
Iron Oxide NP ... 190
Zero-Valent Nanoparticles ... 190
Iron Nanoparticles ... 190
Silver Nanoparticles ... 190
Biosorbents ... 191

C-based Nanoparticles 191
Carbon Nanotubes (CNTs) 191
Graphene 192
TYPES OF ADSORPTIONS STUDIES 192
Adsorption Isotherms 193
Types 193
Langmuir Adsorption 193
Freundlich Isotherm 194
Temkin Isotherm 194
Brunauer, Emmett, and Teller (BET) Isotherm 194
Redliche -Peterson Isotherm 194
Koblee - Corrigan Isotherm 195
Sips Isotherm 195
Toth Isotherm 195
Dubinine - Radushkevich Isotherm 195
Fritze - Schlunder Isotherm 195
Radkee - Prausnitz Isotherm 196
Dubinin - Radushkevich Isotherm 196
POLLUTANTS AND THEIR REMOVAL USING NANO-ADSORBENTS 196
Heavy Metals 196
Organic Compounds 196
Nutrients 197
Emerging Pollutants 197
Pathogens 197
Electrostatic Interactions 197
Complexation 197
Chemisorption 198
π-π Interactions 198
Size Exclusion 198
LONG-TERM EFFECTS OF NANOSORBENTS IN THE ENVIRONMENT 198
CONCLUSION 199
LIST OF ABBREVIATIONS 200
ACKNOWLEDGEMENTS 200
REFERENCES 201

CHAPTER 9 NANOFILTRATION IN WASTEWATER TREATMENT 209
Roopa Rani, Harsha Devnani, A. Jayamani and *Arpit Sand*
INTRODUCTION 209
FUNDAMENTALS OF MEMBRANE FILTRATION PROCESS 210
NANOFILTRATION 212
Mechanism 213
Thin-Film Composite Membranes 215
Nanoporous Membranes 216
Nanocomposite Membranes 217
Nanotube Membranes 218
Nanofiber Membranes 219
Mathematical Modelling 220
Use of Polymers in Nanofiltration 222
FILTRATION AND FOULING OF MEMBRANE 223
Membrane Selection 223
Membrane Configuration 223

Filtration Mechanisms ... 223
Operating Conditions ... 223
Membrane Fouling ... 223
MITIGATION STRATEGIES ... 224
Chemical Cleaning ... 224
Backwashing ... 224
Membrane Modification ... 225
Operational Optimization ... 225
NANOFILTRATION IN SURFACE AND GROUNDWATER ... 225
Fouling Control ... 225
Physical Fouling ... 225
Chemical Fouling ... 226
CONCLUSION ... 226
LIST OF ABBREVIATIONS ... 227
ACKNOWLEDGEMENTS ... 228
REFERENCES ... 228

CHAPTER 10 ZEOLITES IN WASTEWATER TREATMENT ... 234
Vishaka Chauhan, Chinmay Mittal, Chanchal Vashisth and *Neera Raghav*
INTRODUCTION ... 234
CHEMISTRY OF ZEOLITE COMPOUNDS FOR THE REMOVAL OF HEAVY METALS ... 236
CHEMISTRY OF ZEOLITE COMPOUNDS FOR THE REMOVAL OF ORGANIC DYES 241
CONCLUSION ... 254
LIST OF ABBREVIATIONS ... 254
ACKNOWLEDGEMENTS ... 254
REFERENCES ... 254

SUBJECT INDEX ... 259

FOREWORD

I am pleased to write the foreword for the book ***"Nanotechnology for Wastewater Treatment"*** edited by ***Dr. Anjaneyulu Bendi***. This book marks a significant advancement in environmental science, focusing on the innovative application of nanotechnology to address critical wastewater treatment issues. As global environmental challenges intensify, especially concerning water pollution, the need for advanced technologies to provide practical solutions has never been more urgent. Nanotechnology emerges as a transformative force in this arena, promising to revolutionize the treatment and purification of wastewater through its cutting-edge approaches.

The chapters in the book are well-written to represent the most recent findings and advancements in nanomaterials and their applications. The book comprehensively examines numerous nanotechnological techniques to enhance wastewater treatment effectiveness and sustainability. Every chapter provides insightful analysis of practical elements, laying the groundwork for more in-depth study and creative thinking. The collective expertise of the authors and the editorial team has resulted in a work that is both enlightening and inspiring.

I am confident that ***"Nanotechnology for Wastewater Treatment"*** will be an invaluable resource for researchers, practitioners, and policymakers, fostering further exploration and contributing to a more sustainable future for our global water resources.

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PREFACE

Is nanotechnology beneficial for wastewater treatment?

Nanotechnology offers significant benefits for wastewater treatment by providing innovative solutions to remove contaminants more effectively than traditional methods. Nanomaterials can adsorb, break down, and filter out pollutants at the molecular level due to their unique properties. Water treated and made safer by these substances can effectively target and eradicate microorganisms, heavy metals, and organic contaminants. Furthermore, nanotechnology can minimize operating costs, consume less energy, and improve the efficiency of current treatment methods. Wastewater treatment can be made more sustainable and effective by utilizing the enhanced properties of nanomaterials, thereby tackling critical environmental issues and enhancing public health.

Modern experimental research on various nanomaterials used in wastewater treatment is highlighted in this book. **Chapter 1** outlines the recent advancements in nanotechnology for wastewater treatment, highlighting the innovative approaches and techniques that have emerged. It explores how nanomaterials are being utilized to improve the efficiency and effectiveness of removing contaminants from wastewater. **Chapter 2** discusses the precise applications of zero-valent metal nanoparticles in wastewater treatment with particular emphasis on removing heavy metals and dye degradation, which poses a significant risk to human health and the environment.

Metal oxide nanoparticles play an essential role in wastewater treatment because they improve the removal of pollutants via catalytic, adsorption, and degradation processes. Using them in wastewater treatment is an essential advancement toward practical and sustainable water purification techniques, and hence, the significance of metal oxide nanoparticles has been thoroughly discussed in **Chapter 3**, and **Chapter 4** offers a thorough summary of the latest developments, difficulties, and potential uses of carbon nanotubes and their composites in wastewater treatment.

Chapter 5 highlights the use of graphene-based nanoparticles in wastewater treatment, focusing on their unique properties and effectiveness. This chapter explores their role in enhancing pollutant removal and advancing sustainable water purification methods, and **Chapter 6** focuses on the use of carbon-based nanomaterials, including fullerenes, carbon quantum dots, and nanodiamonds for dye degradation and heavy metal removal from wastewater.

In **Chapter 7**, the authors focus on exploring the chemistry of metal-oxide-based nanocomposites and their relevance for the eradication of heavy metal ions and organic dyes from polluted water. **Chapter 8** examines the properties of various nanosorbents and the sorption methods employed for the removal of pollutants from wastewater.

Information on upcoming aspects of the nanofiltration process is provided in **Chapter 9**, which is anticipated to address present and future problems with water treatment and open the door to cleaner and safer water supplies globally, and **Chapter 10** aims to shed light on the extensive research on the creation and use of both natural and manufactured zeolites in the effective removal of diverse pollutants from wastewater.

In conclusion, this book aims to provide a comprehensive overview of the innovative research efforts in the design and synthesis of novel nanomaterials for wastewater treatment. I hope that the content will captivate the interest of aspiring researchers worldwide and inspire them to continue exploring novel nanomaterials for treating various types of wastewater. Additionally, I hope that this book will serve as a valuable resource for researchers, academics, and industry professionals with a strong interest in this field.

I would like to express my profound admiration and gratitude for the dedicated efforts of all the authors who have tirelessly prepared the content of this book. Additionally, I extend my heartfelt thanks to the publisher and its staff for their efficient management of the project at every stage. Finally, I wish to acknowledge my family members for their unwavering support throughout this entire journey.

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CHAPTER 1

Role of Nanotechnology in Wastewater Treatment

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Abstract: Earth's water is a valuable and finite resource, continually recycled through the water cycle. Wastewater is defined as water that has been contaminated with organic and inorganic elements, heavy metals, pathogens, or other toxins that have changed its chemical, physical, or biological properties and made it dangerous for the ecosystem. It is impossible to overestimate the importance of technology innovation in enabling integrated water management. With the safe use of non-traditional water sources, nanotechnology has the potential to significantly increase the efficiency of water and wastewater treatment while also increasing water supply. Several types of nanomaterials are utilized for wastewater treatment, depending on the kind of contaminants and the required level of treatment efficiency. Novel and emerging nanomaterials are emerging together with the field of nanomaterial development. This chapter outlines the recent advancements in nanotechnology for wastewater treatment.

Keywords: Nanotechnology, Nanomaterial, Photocatalysis, Reverse osmosis, Wastewater treatment, Zeolites.

INTRODUCTION

While several materials are required for life's survival and development, water is the most fundamental. Earth is called a "blue planet" because water surrounds more than 70 percentage of its facets. About 97.5 percentage of water is thought to be saline, with the remaining 2.5% being considered pure water, of which 68.9% is found in the form of glaciers, ice, and permanent snow [1 - 7]. In addition, only 0.3% of pure water is readily accessible, with ground water making up 30.8% of the total [8 - 12]. Scientists are still looking into many new innovations to improve inexpensive ways of water filtration [13, 14]. Recently, the field of developing nanotechnology has offered the possibility of removing contaminants from water at a reduced cost, with a high removal effectiveness of impurities and the capacity to be reused [15]. Because of their distinctive active surface area, nanotechnologies can be very significant. Nanomaterials, on the other hand, can be used for extensive purposes, including catalytic membranes,

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Anjaneyulu Bendi (Ed.)

nano sorbents, bioactive nanoparticles, and metal nanoparticles like titanium oxides, iron, and silver [16]. Nanomaterials usually have a size that varies from 1-100nm. Because of their tiny size, they have significantly less atoms than bulk materials, which gives them a very wide range of properties. Because of their tiny size, nanomaterials have an extraordinarily large ratio of surface area in relation to volume, leading to increased surface-relying properties. It has been put in place that due to their dominant physicochemical characteristics, nanoparticles are effectively penetrable for a diversity of water adulterants [17 - 22].

Measurements, including the capacity for adsorption, elimination proportion, disintegration rate, and the rate of reaction, are used to gauge how well nanomaterials eliminate contaminants. Important measurements of performance consist of:

The Elimination Effectiveness

The proportion of treated samples with a lower pollutant concentration.

The Regeneration and the Possibility of Reuse

Cyclic testing evaluates how well a nanomaterial continues to function. The following are several applications.

A Catalytic Activity

The rate at which pollutants degrade under particular circumstances (such as UV exposure) is frequently used to gauge the effectiveness of photocatalytic devices.

The Adsorption Capacity

It is the quantity of the pollutant consumed, which is usually expressed in milligrams per gram of nanomaterial. These data are also impacted by surroundings like pH level, temperature, and contaminant content [23].

Technological developments in nanomaterials have revolutionized water treatment methods, making it possible to safely use unconventional water sources like polluted water, brine water, and saltwater. By enhancing the filtration process, contaminant deterioration, bacterial oversight, and tracking, these materials improve purification and provide more effective, economical, and environmentally friendly options. A summary of their efforts is provided below:

Enhanced Pollutants Elimination for Reusing Wastewater

The elimination of toxic metals, organic contaminants, and medication leftovers is enhanced by the improved process of oxidation and catalytic qualities of nanomaterials.

Control of pathogens and the infection: Excellent antibacterial qualities of nanomaterials provide secure drinking water by removing microorganisms from unconventional sources.

Better Brackish Water and Seawater Desalination

By enhancing the membrane efficiency, decreasing energy usage, and minimizing dirt, nanoparticles improve salinity.

Thin-film Nanocomposite (TFN)

The permeability and rejection of salts are increased when nanoparticles, such as carbon nanotubes and graphene oxide, are embedded in membranes.

Photothermal Nanomaterials

By successfully converting daylight into energy that evaporates liquid, materials such as carbon-based nanocomposites allow solar desalination.

Nanocoating that Prevents Fouling

The longevity of membranes is prolonged by anti-fouling nanocoating, which is composed of titanium dioxide (TiO_2) or silver nanoparticles and limits the growth of bacteria and scalability.

Energy-Saving Water Treatment Methods

Desalination and filtration are made environmentally friendly by the use of nanomaterials in the creation of low-energy methods of treatment. By promoting the electro-sorption of salts, carbon nanomaterials improve the effectiveness of CDI and provide a more environmentally friendly substitute for the process of reverse osmosis. Uninterrupted desalination using sunlight is made possible by photothermal nanomaterials, which speed up the evaporation of water. By improving the heating conductivity and decreasing pore wetness in membranes, nanoparticles increase the energy efficiency of distillation [24].

In order to highlight the possible use of these approaches to address various issues faced by the current wastewater treatment technologies, this chapter primarily examines some recent breakthroughs and utilization of nanotechnology in tainted

CHAPTER 2

Chemistry of Zero-Valent Metal Nanoparticles in Wastewater Treatment

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Abstract: The chapter "Chemistry of Zero-Valent Metal Nanoparticle in Wastewater Treatment" offers a thorough glance at the synthesis, basic chemistry, and utilizations of zero-valent metal nanoparticles, explicitly nano zero-valent iron (nZVI), in the field of wastewater treatment. These nanoparticles have particular qualities, including a huge surface area, magnetic properties, redox potential, and reactivity, that make them an important asset for natural remediation attempts like soil remediation, groundwater treatment, and wastewater treatment. Dye wastewater is a major environmental and health concern because of its negative impacts on aquatic life. Dyes can pose serious health risks to humans and other animals due to their possible toxicity, carcinogenicity, and teratogenicity. Thus, it is essential to make industrial wastewater free from dyes before releasing it into the environment. Moreover, heavy metals are extremely harmful and can cause serious medical conditions when present in water. Inorganic anions in wastewater also pose significant environmental challenges, including the contamination of water resources, negative impacts on aquatic life, and potential risks to human health. This study features the particular utilization of nZVI in wastewater treatment, including the debasement of dyes, heavy metals, and inorganic anions subsequent to breaking down their major natural and well-being concern.

Keywords: Dyes, Environmental remediation, Sustainable development, Wastewater treatment, Zero-valent metal nanoparticles.

INTRODUCTION

Zero-valent metal nanoparticles (NPs) are nanoparticles made up of a metal in its zero-oxidation state, indicating that the metal atoms have not undergone oxidation and remain in their form with no charge. These nanoparticles are typically very small, ranging from 1 to 100 nanometers in diameter. Various methods can be used to develop zero-valent metal nanoparticles, including reduction, electrochemical techniques, and friendly approaches using plant extracts or

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microorganisms. The chosen synthesis method can impact the size, shape, and stability of the nanoparticles. Zero-valent metal nanoparticles possess properties that are different from those of their counterparts. Their high surface area, tiny size, and quantum effects all contribute to improved optical properties. These distinctive features make them highly valuable for a range of applications, such as catalysis, biomedical applications, environmental restoration, and electronics. Examples of zero-valent metal nanoparticles include zero-valent iron (ZVI), zero-valent copper (ZVCu), zero-valent silver (ZVAg), and others. Nano zero-valent iron (nZVI) is a kind of zero-valent metal nanoparticle that has gained attention due to its exceptional characteristics and diverse applications. The characteristics that make nZVI stand out among zero-valent metal nanoparticles, especially in specific situations, are as follows:

Reactivity

nZVI (nano-iron) has a high reactivity. Because of its small size and large surface area, it has greater numbers of active sites than other catalysts. Therefore, the environmental remediation factor of nZVI in various contaminants is very effective at catalyzing the reduction. It is especially used as a way to degrade chlorinated solvents and other organic pollutants.

Magnetic Properties

nZVI particles are usually magnetic, so it is easy not to lose them to reaction sites. This property is convenient for the removal of active nZVI particles, making their use especially advantageous in environmental applications.

Redox Potential

The redox potential of nZVI is suitable for the reduction of different pollutants. This property matters where we want to remove a particular contaminant from water or in other applications such as bioremediation.

Surface Modification

The surface of nZVI nanomaterial can be modified to improve its stability, reactivity, and selectivity. Surface modification techniques include coatings and attachment of functional units that allow the properties of nZVI to be tailored for different applications.

Synthesis Techniques

There are various methods of synthesizing nZVI for different purposes. nZVI synthesis can be optimized by researchers to control the size, shape, and surface properties of nZVI, depending on the planned application [1].

REDUCTION MECHANISM

Nano zero-valence iron (nZVI) can be reduced by transferring the valence from the iron zero particles to other chemical species, thus reducing them. In various applications, especially environmental remediation, this is a crucial mechanism for nZVI to work. The reduction reaction catalyzed by nZVI is dependent upon the contaminants in any one system. The general process for nano zero-valent iron reduction mechanisms is as follows:

- **Electron Transfer**:

The dominant part of the reduction mechanism is the allocation of electrons from zero-valent iron (Fe^0) nanoparticles to other chemical species. This process consists of the oxidation of iron, where iron donates electrons.

$$Fe^0 \longrightarrow Fe^{2+} + 2e^-$$

- **Reducing Contaminants**: For example

Chlorinated Compounds: In the context of environmental remediation, nZVI is often used to reduce chlorinated compounds, such as chlorinated solvents. As nZVI electrons pass between the chlorinated compounds, they are all reduced and dechlorinated.

Heavy Metals: nZVI has the ability to reduce certain heavy metal ions. For example, in the reduction of hexavalent chromium Cr (VI), the reaction entails the transfer of electrons to reduce Cr (VI) to less toxic Cr (III).

$$Cr^{6+} + 3e^- \longrightarrow Cr^{3+}$$

- **Formation of Iron Oxides/Hydroxides**:

Iron oxide/hydroxide species may form on the surface of nZVI particles upon reduction. These species have the potential to impact nZVI's stability and reactivity.

The first test of nZVI for the treatment of polluted water took place in the USA by Wang and Zhang from Lehigh University in 2006, who were attracted by its unique characteristics. After that, it was demonstrated that nZVI is highly efficient at destroying and removing numerous types of chemical pollutants, such as

CHAPTER 3

Metal Oxides Nanoparticles in Wastewater Treatment

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Abstract: A rise in industrial and human activity degrades the quality of the water. This implies that wastewater from residential and commercial properties needs to have pollutants removed. The effectiveness of water filtration and decontamination can be greatly enhanced using nanotechnology. Nanomaterials are effective at killing microbes and eliminating heavy metals and organic and inorganic pollutants from wastewater. Because of their special qualities, namely their vast surface areas and low concentration, metal oxide nanoparticles offer a lot of potential for treating contaminated water. Metal oxide nanoparticles and their uses for eliminating heavy metals and dyes from wastewater, as well as their antibacterial properties, are covered in this chapter.

Keywords: Anti-microbial activity, Dye degradation, Heavy metal, Nanocomposite, Nanoparticles, Wastewater treatment.

INTRODUCTION

The demand for clean water has increased significantly worldwide in recent years due to technology and population development. Seven hundred and eighty three million people lack access to safe water worldwide [1 - 5]. This has led to an urgent search for environmentally acceptable and energy-efficient wastewater treatment techniques. Diverse methodologies have been devised to eliminate these contaminants. Nonetheless, the selection of suitable media is largely responsible for the efficacy of these water treatment methods. Because harmful compounds seep into the process water, the majority of commercially available and chemically synthesized materials used in water treatment also pose extra risks. The selection of materials and optimal techniques for combining them to mitigate the pollution caused by dyes and heavy metals are the main points of emphasis.

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The biological approach is a cost-effective option for producing nanoparticles, including zinc oxide, titanium, aluminum, silver, and nickel oxide nanoparticles. The production of non-toxic end products, low energy consumption, and environmental friendliness make biological synthesis of nanoparticles the preferred method. One of the safest, most straightforward, and least expensive methods for removing dyes, heavy metals, and organic compounds from water contaminated by homes and businesses is photocatalytic degradation, which is based on heterogeneous semiconductors [6 - 10]. Numerous metal oxide nanoparticles (NPs), including CuO, TiO_2, and ZnO, are of concern for their ability to remove heavy metals and photodegrade toxic colors [11 - 21] (Fig. **1**).

CHEMISTRY OF METAL OXIDES FOR THE REMOVAL OF HEAVY METALS

Muhammad Kaleem et al. synthesized iron oxide nanoparticles by using cyanobacteria extract. Initially, cyanobacteria were first mixed with water and heated at 373k for 24 h to prepare the extract, followed by the addition of Nostoc sp. MK-11 and $FeCl_3$. Finally, the mixture was heated for 2 h at 343k to obtain nanoparticles.

Synthesized particles were characterized using various techniques. XRD confirmed the crystalline nature with a crystallite size of 18.21 nm, and SEM images showed a spherical or cubic shape. EDX technique showed the presence of constituent elements, and FTIR peaks confirmed the presence of cyanide, C=O, S=O, O-H, C=C, C-H, C-Cl, and Fe-O bonds. UV spectra peak at 348 nm with strong intensity showed effective synthesis of nanoparticles.

All the above characteristics enable nanoparticles to have a large adsorption surface area, due to which they are used to remove heavy metals Cd and Pb with the efficiency of 85 and 95%, respectively, *via* pseudo-second-order kinetics (Scheme **1**) [22].

Nazia Hossain *et al.* introduced a novel thermos-chemical conversion technique to prepare solvochars of silver nanoparticles as represented in the scheme.

Several spectroscopic techniques were used to analyze crystalline nature, morphology, and functional groups. The BET technique analyzed the porosity and roughness of particles, and XRD confirmed that the FCC structure had an irregular shape and crystalline nature. FTIR data showed the presence of C=C, C-O-C, C-OH, S=O, P=O, C-F, and Si-O-Si bonds. XPS confirmed the presence of constituent elements Mg, Si, Al, *etc*. These nanoparticles were also tested for antibacterial activity and showed strong inhibition against *E. Coli* and *S. aureus*.

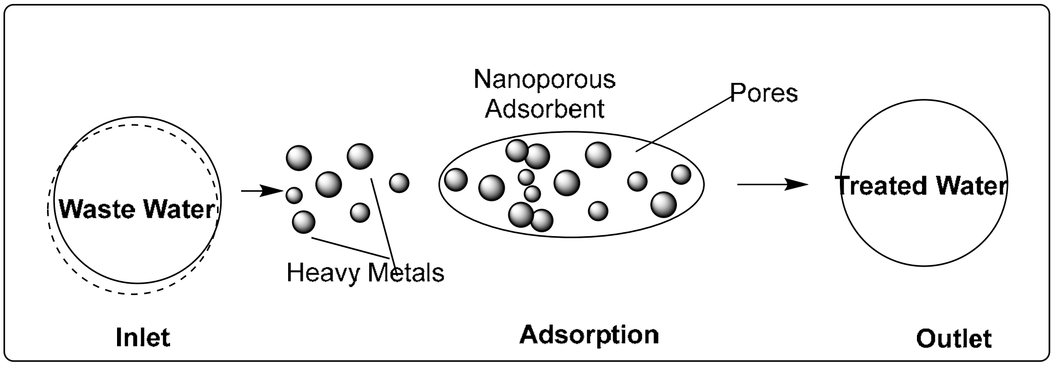
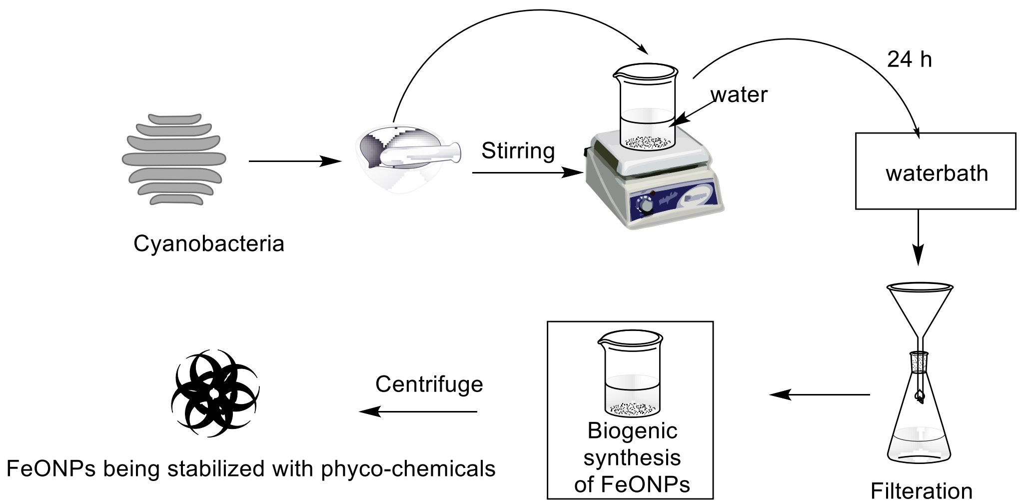


Fig. (1). General mechanism of heavy metal removal from wastewater.



Scheme 1. Synthesis of iron oxide nanoparticles.

These nanoparticles, due to their antibacterial activity and large surface area, were used for water treatment and tested for the removal of heavy metals like copper, iron, lead, zinc, and manganese. (Scheme **2**) [23].

Omolbanin Hosseinkhani *et al.* synthesized graphene oxide-ZnO nanocomposites by mixing ZnO nanoparticles in an ethanol-water mixture followed by the addition of graphene oxide paste and NaOH and heated at 85^{0}C for 5 h. Synthesized nanocomposites were characterized using techniques like XRD and SEM. XRD showed the formation of pure particles without any impurities, and SEM images confirmed the uniform distribution of particles without their agglomeration. These nanocomposites, due to their large surface area, were used as degrading agents and tested for the removal of heavy metals from wastewater. These nanocomposites showed high efficiency in the removal of

CHAPTER 4

Carbon Nanotubes in Wastewater Treatment

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Abstract: The growing worldwide water problem in recent years has highlighted the critical need for creative and effective wastewater treatment solutions. Since carbon nanotubes (CNTs) exhibit special structural, mechanical, electrical, and chemical capabilities, they have become more attractive options. This chapter offers a thorough summary of the latest developments, difficulties, and potential uses of CNTs and their composites in wastewater treatment. We go over the synthesis processes, characterization methodologies, and the effects of many parameters on treatment efficiency, including CNT type, shape, functionalization, and composite formulations. Furthermore, we investigate the regulatory landscape, toxicological issues, and environmental consequences related to the broad use of CNT-based technology in wastewater treatment. To fully realize the promise of CNTs and their composites for sustainable and effective wastewater treatment, this study attempts to compile the state-of-the-art, highlight research gaps, and offer guidance for future studies.

Keywords: Adsorption, Carbon nanotubes, Catalytic degradation, Environmental implications, Membrane filtration, Photocatalysis, Wastewater treatment.

INTRODUCTION

Wastewater treatment is one of the most important problems facing environmental science and engineering today. Wastewater creation has reached previously unheard-of heights due to growing urban populations and industrial activity, endangering both public health and water supplies. Though they have clearly made progress in reducing pollution, conventional wastewater treatment methods frequently fail to meet strict water quality criteria and manage newly emergent pollutants. In this regard, the application of nanotechnology has shown promise as a means of transforming wastewater treatment procedures.

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Recent years have seen a significant increase in interest in carbon nanotubes (CNTs), which have the potential to revolutionize wastewater treatment due to their exceptional physicochemical features and multifunctionalities [1 - 4]. The remarkable mechanical strength, chemical stability, large surface area, and nanoscale dimensions of these materials make them very suitable for a range of environmental remediation applications, including wastewater treatment. To better understand carbon nanotubes' mechanics, applications, difficulties, and potential uses, this chapter will present a thorough overview of the state-of-the-art in this field.

The basic characteristics and methods of carbon nanotube production will be covered in detail in this chapter. To maximize their effectiveness and customize them for particular wastewater treatment applications, it is essential to comprehend the synthesis pathways and structural complexities. Engineering new materials with improved functions is made possible by the variety of morphologies and characteristics of carbon nanotubes, ranging from single-walled to multi-walled forms [5 - 11].

Explaining the fundamental relationship between carbon nanotubes and pollutants in wastewater will be the next area of emphasis. A wide range of contaminants found in wastewater may be efficiently sequestered, broken down, or transformed by CNTs because of their special physicochemical characteristics, which also include their high adsorption capacity, catalytic activity, and capability to promote electron transfer [12 - 16]. For CNT-based treatment systems to be designed effectively and function optimally in a variety of environmental circumstances, it is essential to comprehend these mechanisms.

The broad range of treatment processes that carbon nanotubes may be used in, from membrane filtration and photocatalysis to adsorption and catalysis, demonstrate how versatile these materials are in wastewater treatment [17 - 23]. Their remarkable ability to adsorb permits the elimination of developing contaminants, heavy metals, and organic pollutants from wastewater. Additionally, their catalytic characteristics facilitate the breakdown of resistant pollutants by means of sophisticated oxidation procedures. In addition, the incorporation of carbon nanotubes into membranes presents a significant opportunity to improve the effectiveness and specificity of membrane-based separation procedures, thereby tackling the problem of water shortage and resource retrieval [24 - 29].

The extensive use of carbon nanotubes in wastewater treatment is hampered by a number of issues, including cost-effectiveness, scalability, environmental impact, and regulatory problems, despite their enormous potential. Interdisciplinary research projects, including materials science, engineering, environmental science, and policy-making, are required to address these issues [30 - 35]. In addition, it is crucial to guarantee the sustainable manufacture and disposal of carbon nanotubes in order to avoid any unexpected environmental effects and to guarantee their long-term viability as a wastewater treatment option.

With so much potential, carbon nanotubes have a bright future ahead of them in wastewater treatment. The development of next-generation CNT-based treatment technologies is expected to reach new heights thanks to ongoing developments in functionalization methods, process engineering, and nanomaterial synthesis. Furthermore, combining biotechnology, nanotechnology, and artificial intelligence might lead to the creation of self-governing, adaptive treatment systems that can be optimized and monitored in real time, ushering in a new era of intelligent and sustainable wastewater management [36 - 42] (Fig. **1**).

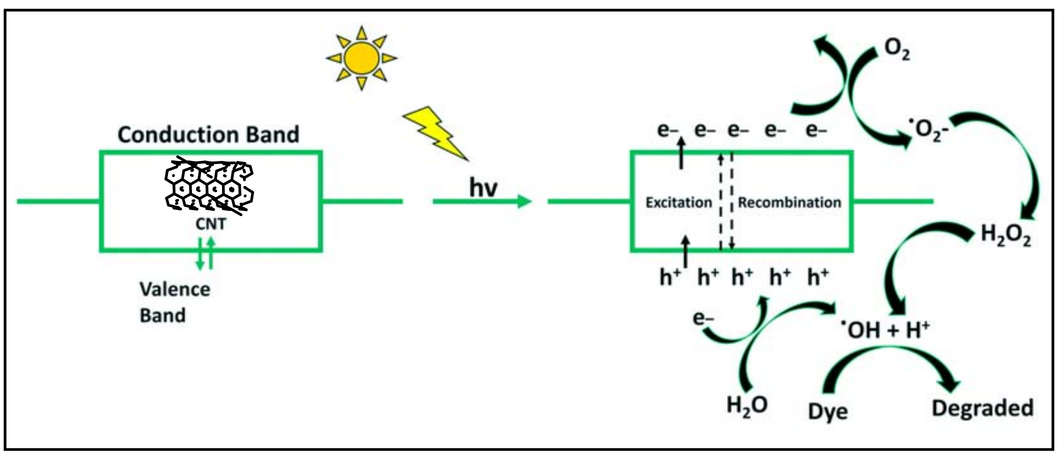

Fig. (1). Degradation of dyes present in wastewater. [37].

To sum up, carbon nanotubes are an innovative technology that might transform wastewater treatment and tackle the growing issues associated with water. This study aims to provide thorough knowledge of the role of carbon nanotubes in advancing state-of-the-art wastewater treatment by clarifying their fundamental features, processes, applications, problems, and future possibilities. Carbon nanotubes have the potential to become essential instruments in the pursuit of sustainable development and clean water *via* coordinated scientific endeavors and tactical partnerships.

CHAPTER 5

Graphene-Based Nanocomposites in Wastewater Treatment

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Abstract: The problem of protecting water, which is a limited resource for future generations, has been brought to light by the startling annual rise in its contamination. Human and environmental health is negatively impacted by an excessive reliance on synthetic chemicals. Sustainable development holds the key to sustaining social and economic development in this concerning situation. The remarkable properties of graphene-based nanocomposite materials, such as their high mechanical strength, large surface area, and versatile reactivity toward polar and nonpolar contaminants, which makes them ideal for broad-spectrum contaminant removal, have led to their selection. This chapter encompasses the utility of these materials in wastewater treatment.

Keywords: Adsorption, Dye degradation, Graphene, Graphene oxide, Heavy metals, Organic dye, Water pollution, Wastewater.

INTRODUCTION

To meet both current and future demands, the world is searching for development that is sustainable due to the faster growth of the global population and the depletion of natural resources [1]. Creating, using, recycling, getting rid of, and eliminating chemicals with the fewest possible adverse effects on human health and the environment are global goals in the field of chemistry. The misuse of artificial chemicals has a negative impact on water, among other things [2, 3]. The most crucial natural resource for maintaining life on Earth is, without a doubt, water.

The estimated amount of wastewater generated annually is 380 billion m^3, and by 2050, this amount is predicted to rise by 51% [4]. Fungicides, industrial effluents, heavy metals, dyes, detergents, soaps, and other substances are the main sources

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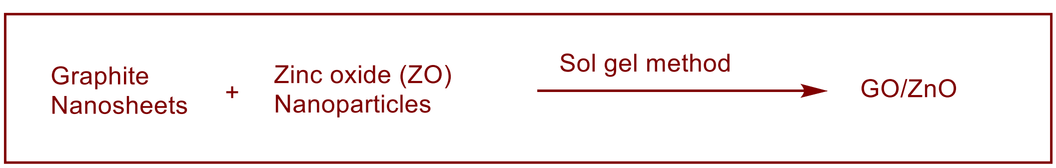
of pollution in water [5 - 11]. The treatment of wastewater is essential to a sustainable future because this can result in a global shortage of water.

Many techniques, including chemical precipitation, ion exchange, neutralization, adsorption, disinfection, and others, have been developed over time for the treatment of wastewater [12 - 16]. These techniques involve the use of chemicals like sodium chlorite, hydrogen peroxide, chlorine, and sodium hypochlorite, among others [17 - 20]. Researching heavy metal removal and dye degradation techniques that are both economical and efficient is humanity's most urgent need.

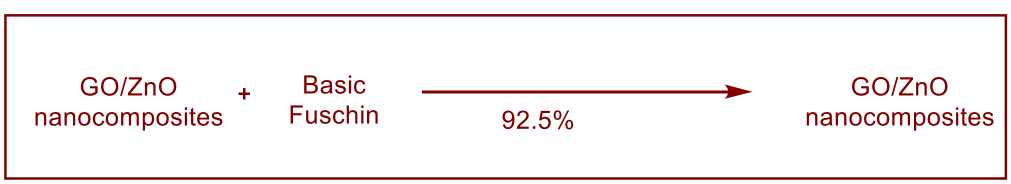
Graphene is a sp^2 hybridized form of carbon with a honeycomb-like structure and conjugated π-bonds, which account for its mechanical and thermal strength [21, 22]. Due to its excellent adsorption capacities, modified graphene has been utilized in water purification, with graphene nanocomposite showing promising ability due to its high efficiency and long-term durability. The presence of different functional groups in these nanocomposites helps remove heavy metal ions and absorb organic dyes from wastewater.

DEGRADATION OF ORGANIC DYES USING GRAPHENE AND ITS DERIVATIVES

Durmus ***et al.*** synthesized a nanocomposite by the amalgamation of graphene oxide (GO) nanosheets with zinc oxide (ZO) nanoparticles for the removal of basic fuchsin (BF) dye. A two-dimensional structure was formed using the sol-gel method with a ratio of GO/ZO of 0.54/0.46 (w/w), and zinc oxide nanoparticles had an average size of 25–30 nm (Scheme **1**). The synthesized nanocomposite showed a degradation efficiency of 92.5% in the first reaction cycle and 84.5% in the fifth reaction cycle, which shows that the nanocomposite can be reused many times [23] (Scheme **2**).

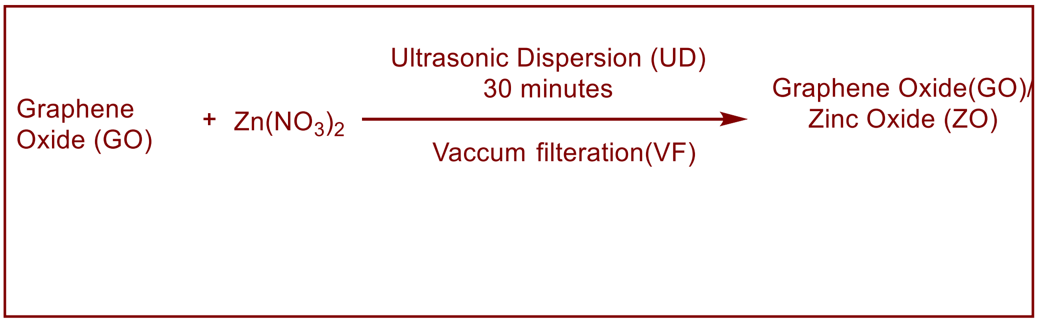


Scheme 1. Graphene oxide and zinc oxide nanocomposite synthesis.

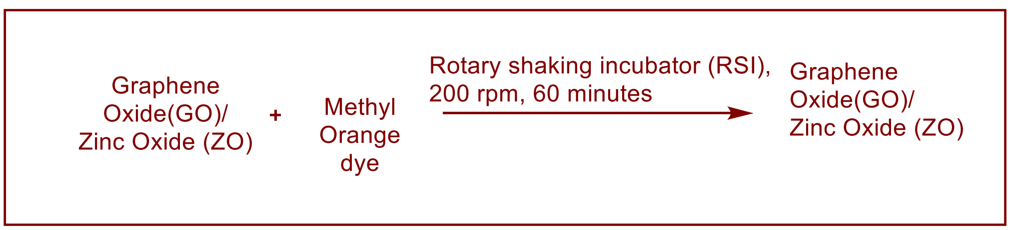


Scheme 2 . Basic Fuschin dye degradation by GO/ZnO nanocomposite.

To make the degradation of methyl orange efficient, ***Wang et al.*** mixed the zinc oxide nanoparticles with porous graphene oxides. The resultant nanocomposite showed excellent photocatalytic activity against the organic dye, removing it 100% in just 150 minutes. The effective charge separation between electron-hole pairs due to the addition of porous graphene with zinc oxide is the primary reason for achieving such high degradation efficiency [24] (Schemes **3** and **4**).

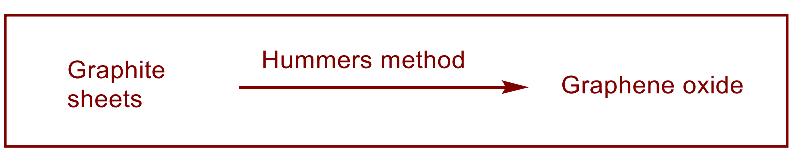


Scheme 3. Formation of graphene oxide/zinc oxide nanocomposite.



Scheme 4. Degradation of methyl orange dye by GO/ZnO nanocomposite.

Khan et al. formed a nanocomposite by combining titanium dioxide (TO) with graphene oxide (GO) in different quantities, *i.e* ., 2%, 4%, 6%, and 8%, having a size of 12.5 nm with a crystalline nature and spherical structure. The results revealed that the synthesized nanocomposite with 8% GO had a larger surface area as well as a narrow band gap, which was the reason for its high and effective catalytic activity against methyl orange and ciprofloxacin [25] (Schemes **5-7**).



Scheme 5. Formation of graphene oxide using Hummer's method.

CHAPTER 6

Carbonaceous Nanoparticles in Wastewater Treatment

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Abstract: Nanoparticles are minute particles with particle sizes ranging from 1nm to 100nm, possessing distinctive physical and chemical properties due to their large surface area and nanosized nature. Nanoparticles, due to their nano size, have unique optical properties, such as adsorption in the visible region, reactivity, and toughness, due to which they tend to be a fit candidate for a variety of commercial and domestic applications. Carbon-based nanomaterials, when combined with nanotechnology are widely used to provide clean and affordable water. Carbon nanomaterials possess properties like positive correlation with specific structural character, alternating dimension factor, mechanical strength, electrical conductivity, *etc*., and hence are used in the application of wastewater treatment. This paper focuses on the use of carbon-based nanomaterials, including fullerenes, carbon quantum dots, and nanodiamonds, for dye degradation and heavy metal removal from wastewater.

Keywords: Carbonaceous nanoparticles, Dye degradation, Fullerenes, Heavy metal removal, Nanodiamond, Quantum dots, Wastewater treatment.

INTRODUCTION

The rapid increase in the global population, coupled with ongoing industrialization, has transformed pollution into a significant and pressing concern. Conservationists have become more worried about effectively managing water due to water pollution. They utilize various methods of treatment, including adsorption, photocatalysis, lignin-based biosorbents, advanced oxidation methods (AOPs), electrochemical treatment, and biological treatments [1 - 5]. Wastewater emerging from industries contains toxins that can be inorganic pollutants (*e.g.*, rare earth metals, heavy metals [Pb, Mn, Ni, Hg, Cd, Co, Cr, Zn, Cu, Sb]) and

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Anjaneyulu Bendi (Ed.)

organic pollutants (*e.g*., phenols, dyes, herbicides, pharmaceuticals, and polycyclic aromatic hydrocarbons (PAH)), which often tend to be carcinogenic and persist longer in environments [6 - 10]. Among all the other wastewater treatment procedures, the adsorption approach has been an encouraging choice due to its high efficiency, ease of large-scale implementation, easy handling and operation, and cost-effectiveness [11, 12].

ROLE OF FULLERENES, NANODIAMONDS, AND CARBON QUANTUM DOTS IN WASTEWATER TREATMENT

Fabrics that are produced synthetically or from natural sources can be colored using dyes. Anthraquinones (red), indigoids (blue), and flavonoids (yellow) are the compounds found in dyes. From 1856 to 1970, mauveine was the first synthetic dye to be used [13]. Dyes such as lactone, indophenol, indamine, azodyes, anthraquinone, phthalocyanine, indigo, xanthene, thiazine, *etc*., are categorized according to their chemical structures which were found in wastewater (Fig. **1**). The most poisonous and carcinogenic of them is azodye, which lowers dissolved oxygen and water transparency [14]. Because dyes contain chromophores and auxochromes in their chemical composition, colored water blocks light penetration and is harmful to aquatic life. Dyes from wastewater can be degraded by a variety of techniques (Fig. **2**).

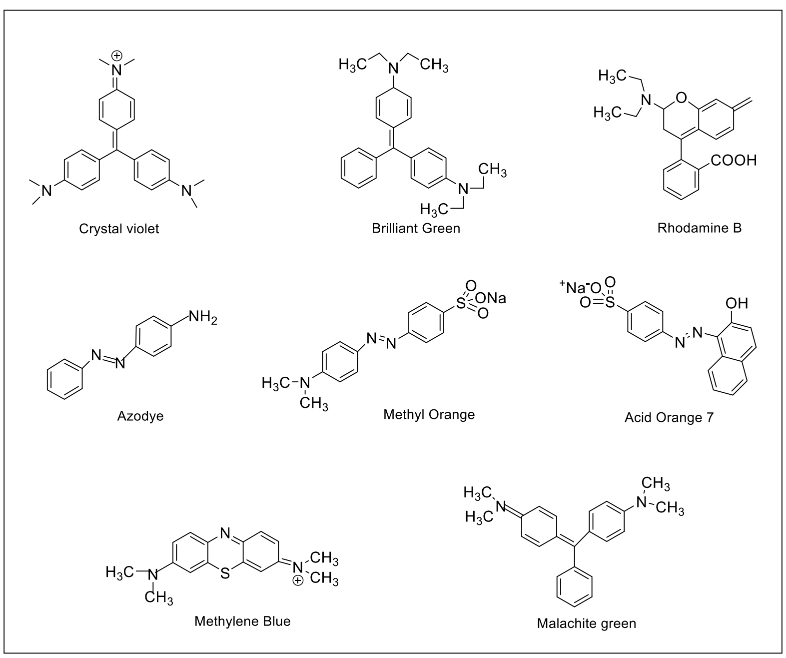

Fig. (1). Structures of some commonly found dyes in wastewater.

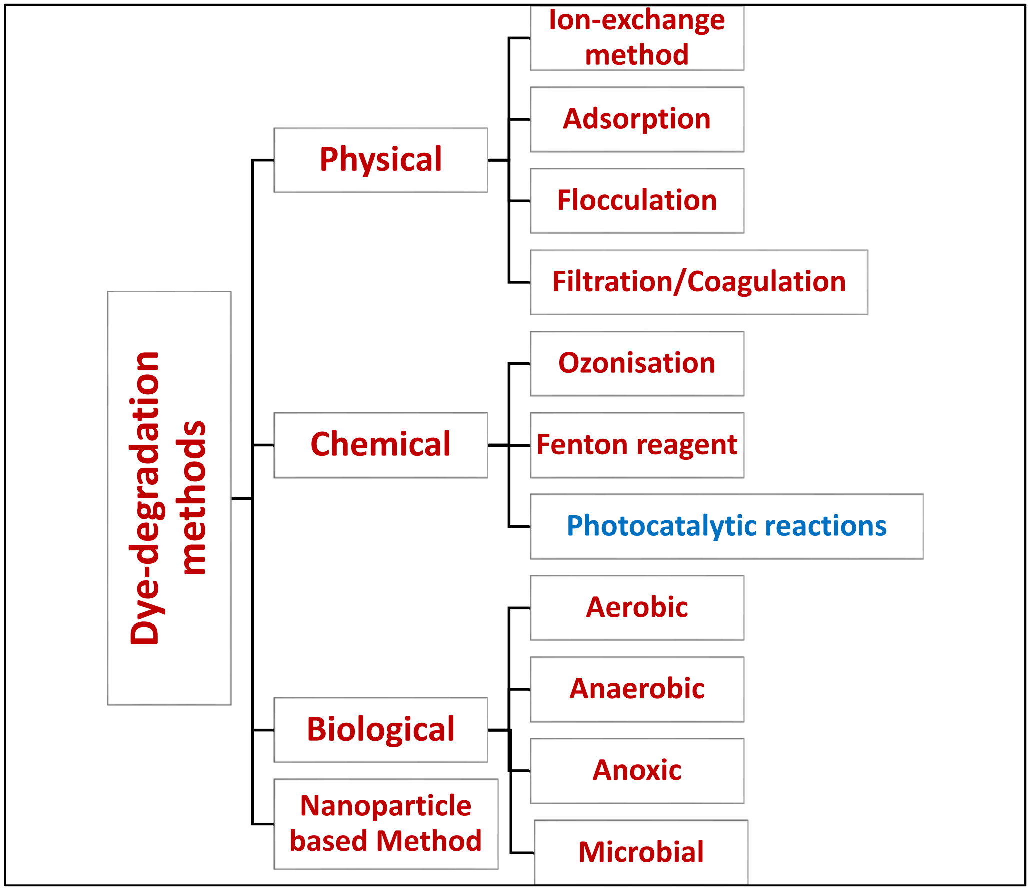

Fig. (2). Methods available for dye degradation.

The global population expansion and increasing industrialization necessitate large amounts of clean water. However, water is becoming more and more contaminated and toxic due to industrial waste.

To turn tainted water into consumable water, multiple methods are used. "Photocatalysis" is among the mentioned. "Carbon-based photocatalysts", which include CNs, NDs, graphene, GCNs, and CQDs [15 - 17], are among the many available photocatalysts (Fig. **3**). Due to their large surface area, high light absorption, excellent stability, ease of use, good porosity, environmental friendliness, ease of preparation, and good band gap, carbon-based photocatalysts are highly preferred. When combined with other semiconductors, the carbon atom functions as an electron sink, essential for improving photocatalytic efficiency [18 - 21].

CHAPTER 7

Nanocomposites in Wastewater Treatment

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Abstract: In recent decades, nanocomposites and their derivatives have been extensively examined to eradicate heavy metals and organic dyes from polluted water. Several methodologies have been introduced to remove heavy metals and dyes. Nanocomposites have been gaining attention, and many nanocomposites have been synthesized to eradicate heavy metals and organic dyes from wastewater because of their outstanding characteristics ensuing from the nanometer end product. In this chapter, metal-oxide-based nanocomposites and their relevance for the eradication of heavy metal ions and organic dyes from polluted water are described.

Keywords: Heavy metals, Nanocomposites, Organic dyes, Wastewater, Water pollution.

INTRODUCTION

The most important water contaminants implicated in various industrial activities are heavy metals and organic dyes, as they cause ecological imbalance and infections in humans and animals due to their accumulation in the organisms. Water effluents pose a massive difficulty in environmental supervision owing to the extensive collection of causes and complex compound composition of toxic waste sources, which are frequently classified as organic and inorganic wastewater [1]; however, in definite water pollution, it is repeatedly a combination of organic and inorganic complex composition, and heavy metals and organic dye components are the most widespread and prominent toxic waste in water pollution [2]. The extensive employment of metallic resources has led to a diversity of heavy metal contaminants like arsenic, lead, chromium, copper, and cadmium, which are a few of the main heavy metal pollutants regularly controlled in the water resources [3]. The pollution of worldly and aquatic environments

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with lethal heavy metals is the most important environmental apprehension that has consequences for civic health. The severe contamination of the environment, human existence, and health troubles caused by heavy metals and organic dyes cannot be disregarded [4]. Therefore, eradicating heavy metal ions and organic dyes from wastewater remains a trendy and attractive research topic. Numerous wastewater treatment procedures with the intention of removing heavy metals and organic dyes have been developed [5] and enhanced throughout time like ion exchange [6], precipitation [7], advanced oxidation process (AOP) [8], lignin-based biosorbents [9], electrolysis [10], photocatalysis [11], phytoremediation [12], and biosorption [13] due to their rapidity, effortlessness of procedure, elevated efficiency, and economical price. In recent years, nanocomposites have experienced a significant responsibility in various industries [14]. Due to their vital function, they are being employed in removing water pollutants from wastewater. In this chapter, we addressed the information regarding eradicating heavy metals and organic dyes from wastewater using nanocomposites.

REMOVAL OF HEAVY METALS FROM WASTEWATER

Umejuru E. C. *et al.* described the applications of nanocomposite material containing zeolite adsorbents for the remediation of wastewater [15]. This research group utilized various materials like carbon, polymers, and metal nanoparticles integrated with zeolite for the elimination of lethal heavy metals and organic dyes from wastewater. The adsorption effectiveness of Pb (II) and As (V) by zeolite/ZnO NCs prepared *via* the co-precipitation method was 93% and 89%, respectively, at pH 4. On the other hand, the removal ability of Pb(II) using zeolite Y/faujasite nanocomposite having a surface area of 19.17 m^2/g was 83.26 mg/g at pH 5.5, and zeolite Y/faujasite coated by cobalt ferrite nanoparticles showed greater adsorption ability of 602.4 mg/g for Pb(II) due to high surface area of 434.4 m^2/g. The adsorption ability of Cr(VI) and Cu (II) from wastewater using fly ash-based zeolite (FZA) incorporated by nano zerovalent iron (nZVI) and nickel (nZVI/Ni@FZA) with a surface area of 154.11 m^2/g was 48.31 and 147.06 mg/g, respectively. Titanium dioxide (TiO_2) incorporated zeolite-4A was used for the removal of Fe(III) and Mn(II) heavy metals, and the adsorption ability was found to be 150.1 and 94.1 mg/g, respectively. Zeolite/Polyvinyl alcohol/sodium alginate incorporated nanocomposites illustrate superior adsorption capacity of Ni(II), Pb (II), Zn, Cu(II), Mn, and Cd, which was 93.1%, 99.5%, 95.6%, 97.2%, 92.4%, and 99.2%, respectively. Moreover, the different zeolite-incorporated nanocomposites (Fig. **1**) have been confirmed to be powerful in the elimination of heavy metals from wastewater.

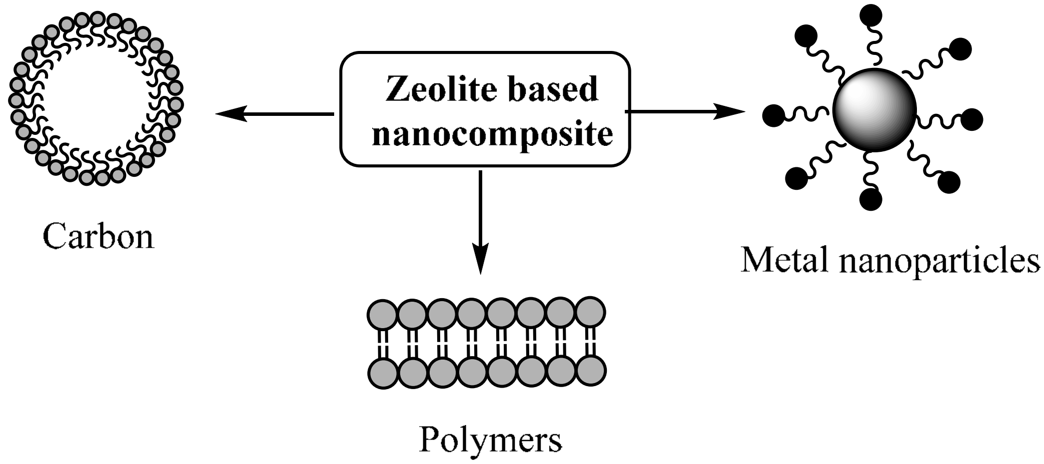

Fig. (1). Zeolite-based nanocomposite using different materials.

Adsorption of reactive orange 16(RO), Congo red (CR), and RO5 in wastewater is carried out by using a nanocomposite of magnetic zeolite/hydroxyapatite (MZeo-HAP). The adsorption of the organic dye system exposed that the nanocomposite material containing functional groups like aromatic, amide, and hydroxyl must contribute to the electrostatic interaction by means of the dyes owing to the positively charged functional groups on CR, RO5, and RO16 with a negatively charged molecule of MZeo-HAP. The sorption capacity of CR, RO5, and RO16 from wastewater is 104.05, 92.45, and 88.31 mg/g, respectively, at pH 2. According to a thermodynamic study, the adsorption capacity of dyes increases with increasing temperature.

Al-Salman *et al.* addressed the preparation of chitosan/graphene nanocomposites [16] for the adsorption of heavy metal ions from wastewater by a solution procedure using various weight percentages of 0.5%, 1.0%, 2.0%, and 5.0%. The preparation of nanographene involves three steps, as shown in (Scheme **1**).

1. *Graphene oxide preparation*
2. *Graphene acylation preparation*
3. *Nanographene preparation*

For the preparation of chitosan grain nanocomposite, first, chitosan solution was added to the functionalized nanophase, followed by magnetic agitation for three days. On the other hand, cross-linked grain nanocomposite was obtained by the addition of formaldehyde and polyethylene glycol, followed by the addition of sodium hydroxide with ethyl acetate to produce granular nanocomposite. The prepared functionalized graphene nanocomposites with an adsorbent phase (25

CHAPTER 8

Role of Nanosorbents in Wastewater Treatment

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Abstract: Nanomaterials must be extensively considered in wastewater management to remove contaminants like heavy metals, pesticides, and dyes owing to their unique properties at the nanoscale. These nanomaterials have greater surface area and tunable surface chemistry, which make them appropriate for use as nanosorbents to gather the contaminations existing in water. The tunable surface properties allow nanosorbents to selectively absorb particular contaminants based on their functionalization. The application of nanomaterials to strengthen the adsorption phenomenon and eliminate numerous pollutants from wastewater has been considered. As the world is struggling for drinkable water and many cities are being declared as dry states, the urge to treat water is increasing continuously. Since the volume of wastewater is increasing day by day, the treatment of wastewater becomes a necessity. The present review includes the study of the properties of different nanosorbents and the method of sorption applied for the elimination of pollutants in wastewater.

Keywords: Adsorption isotherms, Nanomaterials, Nanosorbents, Treatment methods, Wastewater.

INTRODUCTION

Water, which is an indispensable component of the living system, represents the essential component of the existence of life on Earth. It constitutes an important segment that serves as the cornerstone of economics and ecosystems. It is important for nurturing agriculture as it has a pivotal role in the powering industry. Considering the abundance of its utility, the availability of clean and drinkable water is a major concern. About three-fourths of the earth is comprised of water; however, the availability of fresh water for the consumption of living

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organisms is very limited. Mostly, the water content present in the ocean is saline and cannot be used for direct consumption. The treatment of such water systems is necessary to make them fit for domestic, industrial, commercial, and other uses. With continuous rise in populations, rapid urbanization, and industrialization, the demand for fresh and pure water is rising exponentially, resulting in exacerbating pressures on existing water sources. Thus, it generates the necessity to conserve, preserve, and treat used water to fulfill the demand.

Wastewater is generally obtained after utilizing freshwater or potable water for different purposes like washing, bathing, laundry, refinishing of furniture, beauty salons, *etc* [1]. The water obtained after its commercial, industrial, or domestic use (also known as wastewater) may also contain several contaminants and need to be further treated before reusing. Wastewater can also be referred to as used water from several fusions of agricultural, industrial, and commercial activities [2]. As per the surveys of the Central Board of Pollution Control, India, it has been estimated that more than 72 million liters of wastewater per day is generated across the country, out of which only 20% is treated. Treatment of wastewater not only helps solve the water crisis but also plays a significant role in safeguarding public health by reducing the risk of waterborne diseases due to the contaminants present in the wastewater. It supports the protection of the environment by effectively treating the contaminants before entering into rivers and lakes, thus safeguarding the aquatic ecosystems and biodiversity. The effective treatment of wastewater supports the good health of aquatic organisms, ensures safe water for sanitation and recreational purposes, facilitates the responsible management of water resources, and conserves freshwater supplies to reduce pressure on freshwater resources. The main significance of managing wastewater treatment can be focused on water security. Alternate sources of water and rainwater harvesting can be some methods that may satisfy the expected demands of industries and households [3]. The present chapter deals with the methods of treatment of wastewater and also the role of nanomaterials as biosorbents for such treatment.

Water and its Contaminants

Contaminants in water come in diverse forms, ranging from organic pollutants like pesticides and industrial chemicals to inorganic substances such as heavy metals and nitrates. These contaminants often infiltrate water sources through factory releases, agrarian overflow, improper methods of waste dumping, and natural processes like erosion. Once in the water, they provide substantial hazards to human health and the surroundings, potentially causing acute poisoning, chronic diseases, ecological imbalances, and even economic losses. Heavy metals like lead, mercury, and arsenic are predominantly vis-à-vis due to their perseverance and poisonousness, accumulating in aquatic ecosystems and posing long-term health risks to humans and wildlife. Similarly, nutrient pollutants such as phosphates and nitrates, primarily from fertilizers and sewage, can lead to harmful algal blooms, oxygen depletion, and ecosystem degradation in water bodies. Additionally, microbial contaminants like bacteria, viruses, and parasites pose threats to waterborne diseases, especially in areas with inadequate sanitation and water treatment infrastructure. Addressing water contamination requires a multifaceted approach involving monitoring, regulation, treatment, and public awareness. Water quality monitoring programs help identify sources and trends of contamination, guiding regulatory efforts to establish and enforce standards for pollutant levels in water bodies. Treatment machinery such as separation tools, chemical disinfection, and oxidation processes are employed to remove or neutralize contaminants from water supplies, ensuring safe drinking water for communities.

METHODOLOGIES USED FOR WASTEWATER TREATMENT

Water comprises a major part of the Earth's surface. But most of that water consists of a lot of contaminants. These impurities are mostly waste from many industries, dyes, agricultural wastes, and heavy metals [4]. Numerous methodologies can be employed to treat wastewater, each focused on targeting specific contaminants. The initiation step of any treatment methodology includes the physical process involving filtration, screening, and sedimentation of large visible debris to remove it from wastewater. These impurities often show many adverse effects. Hence, it is important to segregate the impurities. There are many techniques used for the separation of waste from water medium. Several factors are typically taken into consideration when choosing a method, including cost, practicality, environmental impact, efficiency, dependability, and operational challenges [5]. The secondary treatment includes the biological processes to break down the microorganisms into environmentally suitable substances. The tertiary and last step for treatment is to disinfect the water with chlorine and other chemicals. Additional upgraded methods like UV disinfection and reverse osmosis can also be used to remove pathogens. Various approaches are adopted to degrade wastewater discharges and address the problems associated with pollutants. The wastewater treatment includes various methods, as represented below in Fig. (**1**) [6].

Direct Membrane Filtration

Direct membrane filtration is the progressive approach for wastewater treatment to filter out the contaminants without involving expensive pre-treatment steps. This method is used to separate impurities by using a membrane. The process

CHAPTER 9

Nanofiltration in Wastewater Treatment

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Abstract: As pure water is considered to be the best medicine in the world, there are serious concerns about water scarcity and water pollution all over the world to find a sustainable way to treat and reuse water. Although traditional wastewater treatment methods are effective, they face problems in terms of adaptability, making them unsuitable and preventing further development. The use of membrane technology in wastewater treatment has received great attention with proven results for removing pollutants, color, and COD/BOD, as well as the reclamation of cleaning solutions. The nanofiltration technique is ahead of all other membrane technologies of wastewater treatment and has more scope for advancements. This book chapter emphasizes the nanofiltration process with more insight into nanofiltration membranes, basic principles involved, mechanism, mathematical modeling of the membrane, use of polymers, and reasons for fouling of membranes used in nanofiltration. The chapter extends its discussion with inputs on the current scenario in the implementation of this technique for surface water, groundwater, fouling control, and effective water reuse. The summary of this book chapter provides information on future aspects of the nanofiltration process, which is expected to address current and future water treatment challenges, paving the way for cleaner and safer water resources worldwide.

Keywords: Fouling control, Membrane filtration, Nanofiltration, Wastewater treatment.

INTRODUCTION

Nanofiltration (NF) in wastewater treatment can be described as a process of membrane filtration where the membrane acts as a barrier to drive the passage of only water molecules and restrict the movement of impurities such as organic, inorganic, and other contaminants [1]. It is a process that falls between reverse osmosis (RO) and ultrafiltration (UF) in terms of pore size. Since the quality of water is continuously degrading day by day, the process of membrane filtration can result in an effective solution for making it reusable [2]. Several studies were reported on the application of nanofiltration for the treatment of wastewater,

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making it suitable for its reuse [3 - 6]. The process of nanofiltration utilizes the concept of semi-permeable membranes to separate ions, molecules, and particles in the molten state. This process is more effective and can be used to treat both groundwater and surface water since it depends on the nature of the membrane, which guides the passage of some selective ions while restricting others. The nanofiltration process is effectively utilized in contamination removal from wastewater, where the removal of organic pollutants, microorganisms, and heavy metals can be done. Another use of the nanofiltration technique is for desalination purposes, especially for treating brackish water sources where the salt content is lower than seawater but still too high for direct consumption or industrial use [7, 8]. NF membranes can selectively remove divalent ions like calcium and magnesium while allowing monovalent ions like sodium and chloride to pass through. This selective permeability helps in achieving partial desalination of water. Nanofiltration can also be used to diminish color and turbidity in liquids. This is particularly important for surface water treatment, where the water may contain natural organic matter and sediments. Many times, NF is combined with RO and has been investigated for wastewater treatment to make it potable. Also, NF can be a pre-treatment step for the process of reverse osmosis and multi-stage flash desalination (RO-MSF), resulting in significant enhancement in the process of desalination, reduction in the load on RO membrane, and improvement of overall efficiency [9]. Nanofiltration also has the advantage of selective filtration or removal of certain ions since they can be easily engineered in this manner. This can be advantageous in treating groundwater contaminated with specific ions or pollutants. NF can also be used for water softening through the selective removal of calcium and magnesium ions responsible for water hardness. This is particularly beneficial in areas where hard water causes scaling in pipes and appliances. This chapter briefly describes the use of nanofiltration in wastewater treatment, along with the details of the steps involved.

FUNDAMENTALS OF MEMBRANE FILTRATION PROCESS

The effectiveness and selectivity of membrane filtering make it a popular separation method across many sectors. Membrane filtration works on the basis of the membrane's semi-permeable nature, which permits some molecules or particles to flow through while obstructing others due to differences in size, shape, charge, or chemical composition. The liquid or solution is forced to pass through the membrane by a pressure differential across it, which is what drives this process and separates the desired components from the feed stream. The size of the particles that can pass through a membrane is determined by the size of its pores; with varying membrane types having different pore diameters and selectivity, multiple filtration can be achieved. Furthermore, the concentration of the feed solution, the pH of the solution, and the temperature can all have an impact on membrane filtration and affect the process's selectivity and efficiency [10].

Membrane filtration is a vital procedure that, by providing effective and selective separation of materials at the molecular and ionic levels, has transformed a number of industries. The type of membrane to choose is important and relies on the demands of the particular application. Microorganisms like bacteria, viruses, and suspended particles are frequently removed using microfiltration (MF) membranes. Their pore diameters, which span from 0.1 to 10 μm, enable them to efficiently eliminate particles falling within this range. The pore sizes of ultrafiltration (UF) membranes range from 0.001 to 0.1 μm, making them effective for the efficient separation of proteins, colloids, and macromolecules from liquids [11, 12]. Nanofiltration (NF) membranes, which have even smaller holes than UF membranes, can be used to remove divalent ions and small organic molecules. Last but not least, desalination and the elimination of small ions and molecules are accomplished using reverse osmosis (RO) membranes, which have the smallest pore sizes—less than 0.001 μm [13].

Depending on the kind of membrane, multi-membrane filtering mechanisms exist. Size exclusion, in which particles bigger than the pore size are trapped on the membrane surface while smaller particles flow through, is the main method of particle removal in MF and UF. By utilizing extra mechanisms like electrostatic attraction and adsorption, NF and RO membranes enable the selective separation of ions and molecules according to their size and charge. This selectivity is essential in applications like water treatment and pharmaceutical manufacturing, where exact separation of particular chemicals is needed [14].

The optimization of membrane filtering operations is largely dependent on operating parameters such as feed concentration, temperature, feed flow rate, and trans-membrane pressure (TMP), which is the pressure differential across the membrane and a vital component that propels filtration. The rate of filtration is affected by the temperature and feed flow rate, with higher temperatures and flow rates typically resulting in higher filtration rates. Feed concentration has an impact on the membrane's performance as well; larger concentrations may result in more fouling [15, 16].

One of the main problems with membrane filtration is membrane fouling, which can shorten the membranes' lifespan and efficiency. It happens as a result of particles, microbes, or dissolved materials building up on the membrane surface and decreasing its permeability. The use of anti-fouling membranes, chemical cleaning, and routine backwashing are methods to reduce membrane fouling. These techniques lower the overall operating expenses of membrane filtering

CHAPTER 10

Zeolites in Wastewater Treatment

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Abstract: The increasing concern over water pollution and the scarcity of clean water resources, amplified by increased urbanization and industrialization, is accompanied by the accumulation of heavy metal contaminants within wastewater systems. This alarming trend poses significant threats to human and environmental health, intensifying the search for efficient and sustainable wastewater treatment technologies. Zeolites, a class of microporous aluminosilicate minerals, have gained attention as a favorable material for the management of wastewater because of their versatility, chemical stability, large surface area, considerable ion-exchange capacity, selective adsorption property, and environment-friendliness that enables them to effectively address several different kinds of contaminants present in wastewater streams. The objective of this book chapter is to bring light to the thorough investigation of the synthesis and application of synthetic and natural zeolites in efficiently removing various contaminants, such as organic dyes and heavy metals, from wastewater. The mechanisms of adsorption and ion exchange are discussed, highlighting the factors affecting the efficiency of zeolites, particularly surface charge, chemical composition, and pore dimension.

Keywords: Adsorption, Heavy metals, Organic dyes, Pollutants, Water treatment, Zeolites.

INTRODUCTION

The urgent worldwide problem of water contamination and shortage demands the creation of novel wastewater treatment technologies. Zeolites are a substance that has shown promise in many ways because of their special qualities and wide range of uses in water cleanup procedures. Zeolites, which are crystalline aluminosilicates with a porous structure and the ability to exchange ions, provide a variety of ways to remove and break down pollutants from aqueous solutions effectively [1 - 5].

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Environmental and public health risks arise from water pollution caused by urban activities, agricultural runoff, and industrial discharges. Alternative solutions are being investigated because traditional wastewater treatment procedures frequently fail to handle the wide variety of contaminants contained in wastewater streams. Zeolites' large surface area, adjustable pore size, and selective adsorption capabilities have drawn interest in their ability to successfully solve this issue [6 - 8].

Since zeolites can adsorb numerous kinds of contaminants, including nutrients, organic pollutants, and heavy metals, this is how they are mostly used in wastewater treatment [9 - 14]. Electrostatic interactions, ion exchange, and molecular sieving processes enable the selective adsorption of target molecules into the microporous structure of zeolites. Additionally, zeolite surfaces can be modified by functionalization or ion exchange procedures, which can improve their selectivity and adsorption capacity and increase their effectiveness in removing pollutants.

Zeolites are adsorbents, but they also have catalytic qualities that may be used to break down stubborn organic materials in wastewater [15 - 23]. Zeolites facilitate the effective conversion of contaminants into lesser hazardous or inert substances by oxidation, hydrolysis, or other chemical transformations by acting as catalyst supports or active sites for heterogeneous catalysis. The combination of adsorption and catalysis on zeolite surfaces provides a holistic method of treating wastewater, efficiently removing both soluble and insoluble pollutants.

Zeolites are also essential for sophisticated procedures for the treatment of wastewater, such as membrane filtration, nutrient recovery, and ion exchange. Because of their molecular sieving capabilities, zeolite-based membranes provide better separation performance by allowing contaminants to be selectively removed while keeping nutrients and necessary ions in place [24 - 33]. Furthermore, by using zeolites' ion exchangeability to remove certain ions or recover valuable materials from wastewater streams, resource conservation and the concepts of the circular economy may be supported (Fig. **1**).

To sum up, zeolites are a flexible and exciting family of materials that may be used to tackle the intricate problems involved in wastewater treatment. Zeolites provide efficient solutions for pollutant removal, catalytic degradation, and resource recovery across a range of wastewater treatment situations owing to their distinct physicochemical features and wide range of uses. The sustainability and effectiveness of wastewater treatment procedures might be greatly increased by carrying out ongoing research to explore new applications and optimize zeolite-based technology.

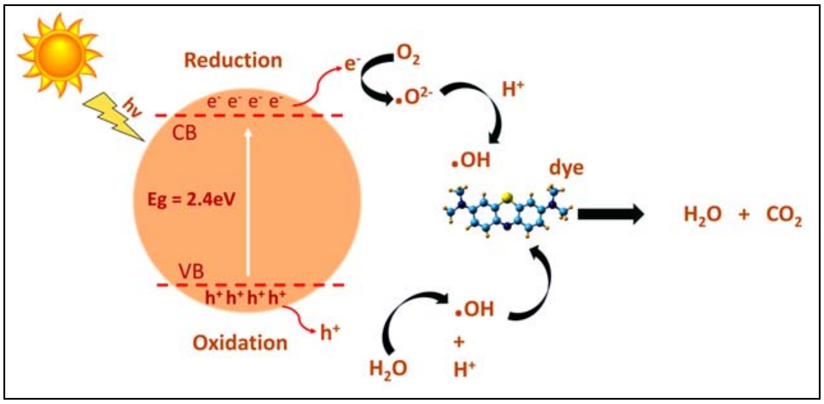

Fig. (1). Degradation of dyes present in wastewater. [30] .

This book chapter provides an in-depth analysis of the uses, underlying processes, and future possibilities of zeolites in wastewater treatment. The goal of this study is to promote sustainable and effective wastewater treatment solutions by clarifying the many functions that zeolites play in water remediation.

CHEMISTRY OF ZEOLITE COMPOUNDS FOR THE REMOVAL OF HEAVY METALS

Sivalingam, S. et al. created zeolite nanocrystalline to remove heavy metals from industrial effluents. (Schemes **1, 2**) [34].

raw fly ash samples (1 + NaOH : 1.25) + HCl (2M) $\xrightarrow{\hspace{2em}}$ nanocrystalline NaX

calcinated at 800°C for 60min., then put in a furnace at 550°C for 90 min.,cooled, then stirred for 2h, and then dried in oven

Scheme 1. Synthesis of nanocrystalline NaX.

Nanocrystalline zeolite NaX (100mg/100mL) + Industrial Effluents (50mg/L) $\xrightarrow{\hspace{2em}}$ Nanocrystalline zeolite NaX

stirring for 30 min., pH= neutral,
162.96mg/g adsorption capacity of Zn(II),
159.25mg/g adsorption capacity of Cu(II),
150.52mg/g adsorption capacity of Cd(II),
171.23mg/g adsorption capacity of Pb(II),
122.26mg/g adsorption capacity of Ni(II),
119.63mg/g adsorption capacity of Ca(II),
and 128.52mg/g adsorption capacity of Mg(II)

Scheme 2. Removal efficiency of heavy metal ions.

SUBJECT INDEX

A

Agglomeration 48, 50, 56,63, 72, 74, 85
Alginate-silicate beads 58
Amination 100
Analytical tools 84, 85
Anisotropic 86
Antibacterial activity 71, 72, 76
Asymmetric membranes 214
Attapulgite 61, 62, 128
Azo dye 34, 35, 38, 39, 40, 41, 42, 43, 44, 46, 81, 83, 188
Auxochromes 138

B

Brilliant green 141, 142
Bioaccumulation 47, 199
Biodiversity 47, 181
Biofouling 191, 224, 226
Bio-molecular solids 224
Biosorbents 17, 137, 156, 181, 191
Biotechnology 1, 95, 223

C

Carbonaceous nanoparticle 4, 14, 137
Carbon 3, 12, 13, 16, 17, 40, 48, 87, 93, 94, 95, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 110, 111, 137, 138, 150, 191, 196, 198, 199, 217, 218
  nanotubes 3, 12, 13, 16, 17, 40, 48, 87, 93, 94, 95, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 110, 111, 191, 196, 198, 199, 217, 218
  quantum dots 137, 138, 150
Carbonization 57
Carboxymethyl cellulose 53
Catalytic degradation 71, 81, 93, 141, 143, 144, 165, 166, 235, 250
Chemical fouling 226
Chromophores 138
Coagulation 4, 7, 8, 9, 48, 183, 184, 213, 224, 225, 226
Coagulants 4, 5, 183, 184
  traditional aluminous 5
  chemical 183
Colloidal 7, 106, 225
  particles 225
  residues 7
  suspension 106
Composite formulations 93
Congo red 14, 39, 43, 45, 78, 79, 85, 86, 157
Co-precipitation 51, 75, 106, 156, 159
Crystalline 21, 39, 42, 49, 53, 71, 74, 75, 77, 78, 79, 81, 82, 86, 119, 141, 146, 234, 236
  morphology 86
  phases 53
  structure 49, 81
  nature 71, 74, 75

D

Desalination, 3, 87, 210, 211, 215, 217, 218, 225
Divalent ions 210, 211, 212
Dye degradation 34, 35, 36, 42, 63, 70, 84, 86, 117, 118, 137, 139, 142, 143, 145, 146, 148, 163, 168, 172, 190, 247, 248, 253

E

EDTA 124
Electrocoagulation 9, 48
Electroplating 48
Electrostatic repulsion 212, 214, 227
Energy-intensive procedures 111, 199

F

Flocculation 4, 5, 34, 183, 184, 213, 225, 226
Fouling control 209, 225
Fullerenes 137, 138, 140, 146, 150
Functionalized carbon nanotubes 99, 100, 106, 107, 108

G

Glutaraldehyde 161
Graphene 3, 4, 13, 40, 44, 51, 52, 72, 74, 77, 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 139, 142, 157, 158, 163, 167, 168, 172, 174, 186, 187, 192, 196, 198, 199, 216, 217, 219
  -based Nanoparticles 4, 13
  oxide 3, 13, 51, 52, 72, 74, 77, 117, 118, 119, 121, 122, 123, 125, 126, 128, 130, 131, 132, 157, 158, 163, 167, 168, 172, 174, 192, 196, 198, 216, 217, 219
Graphite 13, 40, 52, 57, 85, 130, 146, 160
  oxide 160
Gravity-driven membrane 109

H

Heavy metal removal 17, 57, 72, 118, 137
Hybrid nanomaterials 109
Hydrocarbons 10, 11, 138, 196
  aliphatic 11
  polyaromatic 11
  polychlorinated 10
  polycyclic aromatic 138

I

Ion exchange 7, 47, 56, 59, 63, 105, 118, 156, 185, 187, 224, 234, 235, 237, 238, 239, 241, 243
Impregnation 253
Industrial wastewater 14, 31, 34, 46, 87, 101, 166, 173, 174, 237, 238, 241, 243, 253

L

Langmuir model 98, 238, 241
Lepidocrocite crystals 60
Lignin 13, 99, 100, 137, 156, 218
  aminated 13

M

Magnetic solid phase extraction method 22
Malachite green 13, 83, 148
Membrane filtration 8, 34, 48, 93, 94, 109, 182, 183, 209, 210, 211, 212, 219, 223, 225, 226
  direct 182
  gravity-driven 109
Manganese ferrite 121, 122, 126
Metal oxide nanoparticles 70, 71, 77, 84, 87, 88, 188, 189, 196, 197, 199
Methylene blue 43, 45, 78, 79, 81, 82, 109, 120, 122, 123, 141, 142, 144, 146, 148, 150, 192, 254
Methyl orange 37, 40, 41, 42, 43, 45, 119, 121, 132, 141, 147, 192, 254
Mesoporous carbon 99, 159
Microfiltration 40, 211, 224
  electro-catalytic 40
Microstructure 78, 84
  fibrous 84
Morphological structure 77
Monolayer adsorption 105
Multi-walled carbon nanotubes 106, 218

N

Nanodiamond 137, 38, 140, 147, 150
Nanofiber membranes 219, 220
Nano filters 4
Nanofiltration 8, 9, 18, 209, 210-227
Nanorods 20
Nanospheres 85
Nano-spray 77
Nickel oxide 71, 126, 163, 250

O

Organic 3, 6, 10, 11, 14, 17, 18, 32, 46, 166, 190, 197, 237, 239
  contaminants 3, 17, 18, 46, 166, 190, 197, 237, 239
  pollutants 6, 10, 11, 14, 17, 32, 35, 41, 42, 47, 94, 110, 111, 137, 138, 169, 170, 181, 183, 184, 190, 196, 198, 199, 210, 212, 235, 253
Oxidative stress 110
Oxidized arsenic 109

P

Photocatalytic degradation 71, 81, 141, 143, 144, 165, 166, 250
Photocatalysis 1, 9, 19, 20, 93, 94, 137, 139, 156, 166, 243
Photodegradation 80, 81, 141, 146, 162, 165, 170
Polyethersulfone 40, 215
Polydopamine 97
Polymer matrix nanocomposite 16
Polyvinyl alcohol 156, 161
Porosity 13, 18, 71, 84, 139, 187, 194, 219, 247
  high 187, 219
  textural 247

Q

Quantum dots 21, 137, 138, 140, 147, 149, 150

R

Reactive orange 157
Reduced graphene oxide 51, 52, 74, 121, 122, 125, 163, 192
Reverse osmosis 1, 3, 8, 9, 87, 182, 183, 209, 210, 211, 213, 221, 222
Rutile structure 74, 79

S

Scalability 3, 94, 111, 199
Sedimentation 6, 48, 182, 224, 225
Size exclusion 198, 211, 212, 213, 222, 223, 224, 226
Silica nanoparticles 12, 101, 197
Sodium alginate 55, 56, 59, 156, 160, 161
Solvothermal method 96, 109
Sustainable development 31, 95, 117

T

Thin-film nanocomposite 3
Trans-membrane pressure 211
Traditional polymeric membrane 108

U

Ultrafiltration 8, 18, 209, 211, 224
UV Irradiation 145

W

Wastewater Treatment 1, 3, 4, 9, 10, 13, 18, 22, 31, 34, 36, 38, 47, 56, 58, 60-63, 70, 85, 93, 94, 95, 103, 111, 117, 137, 138, 140, 150, 155, 156, 181, 182, 184, 186, 187, 189, 190, 191, 197, 199, 200, 209, 210, 212, 215, 219, 226, 234, 235, 236, 240, 253, 254

Z

Zeolites 1, 4, 7, 21, 48, 125, 197-200, 234-246
Zero-valent metal nanoparticle 10, 31, 32, 45, 63
Zinc oxide 71, 86, 118, 119, 121, 132, 171, 172, 173, 174, 189
  green synthesis 86
Nanocomposite 121

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