



Chemistry in the Environment

Advanced Materials for Emerging Water Pollutant Removal

Edited by Pei Sean Goh, Devagi Kanakaraju, Anwar Iqbal
and Ahmad Fauzi Ismail

Advanced Materials for Emerging Water Pollutant Removal

Chemistry in the Environment Series

Editor-in-chief:

Dionysios D. Dionysiou, *University of Cincinnati, USA*

Series editors:

Rajasekhar Balasubramanian, *National University of Singapore, Singapore*
Triantafyllos Kaloudis, *Athens Water Supply and Sewerage Company (EYDAP S.A.), Greece*
Rafael Luque, *King Saud University, Saudi Arabia*

Titles in the series:

- 1: Graphene-based 3D Macrostructures for Clean Energy and Environmental Applications
- 2: Metallurgical Slags: Environmental Geochemistry and Resource Potential
- 3: Functional Hybrid Nanomaterials for Environmental Remediation
- 4: Emerging Nanotechnologies for Water Treatment
- 5: Biological Treatment of Industrial Wastewater
- 6: Advances in Functional Separation Membranes
- 7: Persulfate-based Oxidation Processes in Environmental Remediation
- 8: Advanced Ozonation Processes for Water and Wastewater Treatment: Active Catalysts and Combined Technologies
- 9: Environmental Nanopollutants: Sources, Occurrence, Analysis and Fate
- 10: Photo- and Electrochemical Water Treatment: For the Removal of Contaminants of Emerging Concern
- 11: Ionic Liquids for Environmental Issues
- 12: Novel Materials and Water Purification: Towards a Sustainable Future
- 13: Microbial Bioremediation and Multiomics Technologies for Sustainable Development: Recent Trends
- 14: Advanced Materials for Emerging Water Pollutant Removal

How to obtain future titles on publication:

A standing order plan is available for this series. A standing order will bring delivery of each new volume immediately on publication.

For further information please contact:

Book Sales Department, Royal Society of Chemistry, Thomas Graham House,
Science Park, Milton Road, Cambridge, CB4 0WF, UK
Telephone: +44 (0)1223 420066, Fax: +44 (0)1223 420247
Email: booksales@rsc.org
Visit our website at books.rsc.org

Advanced Materials for Emerging Water Pollutant Removal

Edited by

Pei Sean Goh

Universiti Teknologi Malaysia, Malaysia

Email: peisean@petroleum.utm.my

Devagi Kanakaraju

Universiti Malaysia Sarawak, Malaysia

Email: kdevagi@unimas.my

Anwar Iqbal

Universiti Sains Malaysia, Malaysia

Email: anwariqbal@usm.my

and

Ahmad Fauzi Ismail

Universiti Teknologi Malaysia, Malaysia

Email: fauzi.ismail@gmail.com



ROYAL SOCIETY
OF **CHEMISTRY**

Chemistry in the Environment Series No. 14

Print ISBN: 978-1-83767-117-5

PDF ISBN: 978-1-83767-542-5

EPUB ISBN: 978-1-83767-543-2

Print ISSN: 2516-2624

Electronic ISSN: 2516-2632

A catalogue record for this book is available from the British Library

© The Royal Society of Chemistry 2024

All rights reserved

Apart from fair dealing for the purposes of research for non-commercial purposes or for private study, criticism or review, as permitted under the Copyright, Designs and Patents Act 1988 and the Copyright and Related Rights Regulations 2003, this publication may not be reproduced, stored or transmitted, in any form or by any means, without the prior permission in writing of The Royal Society of Chemistry or the copyright owner, or in the case of reproduction in accordance with the terms of licences issued by the Copyright Licensing Agency in the UK, or in accordance with the terms of the licences issued by the appropriate Reproduction Rights Organization outside the UK. Enquiries concerning reproduction outside the terms stated here should be sent to The Royal Society of Chemistry at the address printed on this page.

Whilst this material has been produced with all due care, The Royal Society of Chemistry cannot be held responsible or liable for its accuracy and completeness, nor for any consequences arising from any errors or the use of the information contained in this publication. The publication of advertisements does not constitute any endorsement by The Royal Society of Chemistry or Authors of any products advertised. The views and opinions advanced by contributors do not necessarily reflect those of The Royal Society of Chemistry which shall not be liable for any resulting loss or damage arising as a result of reliance upon this material.

The Royal Society of Chemistry is a charity, registered in England and Wales, Number 207890, and a company incorporated in England by Royal Charter (Registered No. RC000524), registered office: Burlington House, Piccadilly, London W1J 0BA, UK, Telephone: +44 (0) 20 7437 8656.

For further information see our website at www.rsc.org

Printed in the United Kingdom by CPI Group (UK) Ltd, Croydon, CR0 4YY, UK

Preface

Water scarcity is an increasing issue on every continent. Along with climate change, the global issue is escalated by urbanization, population growth, and pollution. According to the World Bank report, 80% of wastewater enters water bodies without being adequately treated. The release of vast amounts of industrial and domestic wastewater results in the pollution of the water environment and ecosystem. Proper treatment of these wastewaters allows their reutilization for many purposes and applications including industrial processes and irrigation. Advanced materials are known to be promising tools to alleviate the impacts of these issues. In the last decade, tremendous efforts have been made to progress in the field of synthesis and application of advanced materials especially for use in environmental remediation. Advanced materials including nanomaterials and biomaterials can be used to remove pollutants from water and air. A wide range of advanced materials can be prepared through affordable, energy-efficient approaches. They can also be easily retrofitted in existing wastewater or air filtration systems.

This edited book, *Advanced Materials for Emerging Water Pollutant Removal*, explores the potential of advanced materials to deal with the various kinds of pollutants found in water bodies. This book aims to bring together the ideas and innovations of researchers working in the field, and provides a detailed overview of the development of various functional advanced materials for the removal of emerging pollutants. This edited book comprises eight chapters that focus on the synthesis, characterization, and modification of nanomaterials as well as their applications and evaluation of their performance. The engineering of materials through innovative synthesis and modification approaches allows the fine-tuning and optimization of materials in terms of their functionality and efficiency. With the ever-growing threats of

conventional and emerging pollutants in our water, the advancements made over the past decade could serve as a catalyst in revolutionizing efforts in environmental remediation.

We extend our heartfelt gratitude to all the contributors for their expertise and dedication in completing the chapters. Their insights are substantial in shaping the contents of this edited book. We would also like to thank the publisher for their support throughout the preparation and production processes. Lastly, by harnessing the advantages of a broad range of advanced materials, we aim to not only address the alarming pollution and water scarcity issues, but also contribute to the Sustainable Development Goals particularly Sustainable Development Goal 6: Clean Water and Sanitation. It is hoped that this edited book will provide inspiration and guidelines to propel the research community towards a cleaner and more sustainable future.

Pei Sean Goh
Devagi Kanakaraju
Anwar Iqbal
Ahmad Fauzi Ismail

Contents

Chapter 1	Preparation and Modification of New Functional Materials for Organic Pollutant Elimination	1
	<i>C. Rizzo, S. Amata, G. Emmola, S. Buscemi, A. Pace and A. Palumbo Piccionello</i>	
1.1	Introduction	1
1.2	Biopolymers	3
	1.2.1 Cellulose and Its Derivatives	3
	1.2.2 Alginate	5
	1.2.3 Lignin	6
1.3	Metal and Covalent Organic Frameworks	6
	1.3.1 Removal of Biological Contaminants by MOFs	7
	1.3.2 Removal of Organic Pollutants by COFs and MOFs	8
	1.3.3 Removal of Metal Contaminants by COFs and MOFs	9
1.4	Functionalized Carbon-based Nanomaterials	11
1.5	Hybrid Materials	13
	1.5.1 Silica and Metal Oxide Based Hybrids	14
	1.5.2 Metal–Organic Framework Hybrids	16
	1.5.3 Carbon-based Hybrids	17
1.6	Conclusions	19
	Acknowledgments	19
	References	19

Chemistry in the Environment Series No. 14

Advanced Materials for Emerging Water Pollutant Removal

Edited by Pei Sean Goh, Devagi Kanakaraju, Anwar Iqbal and Ahmad Fauzi Ismail

© The Royal Society of Chemistry 2024

Published by the Royal Society of Chemistry, www.rsc.org

Chapter 2	Synthesis and Functionalization of Advanced Materials for Pollutant Removal	24
	<i>Kalaivizhi Rajappan, Neeraja Bose, Anishia Ambrose and Anwar Iqbal</i>	
2.1	Introduction	24
2.2	Advanced Materials for Pollutant Removal	26
2.2.1	Covalent Organic Framework	26
2.2.2	Metal Organic Framework	26
2.2.3	MXene	27
2.2.4	Bio-based Materials	28
2.3	Functionalization of Advanced Materials	29
2.3.1	Functionalized COF for Pollutant Removal	29
2.3.2	Functionalization of MOF for Pollutant Removal	31
2.3.3	Functionalization of MXene	32
2.3.4	Functionalization of Biochar and Biocomposites	32
2.4	Synthesis Techniques for Advanced Functionalized Materials	33
2.4.1	Solvothermal	33
2.4.2	Hydrothermal	41
2.4.3	Microwave-assisted Method	42
2.4.4	Sonochemical	42
2.4.5	Techniques for Biochar Preparation	43
2.5	Top-down and Bottom-up Approaches	44
2.5.1	Ball-milling	45
2.5.2	Etching	45
2.6	Challenges and Future Prospects	45
2.7	Conclusion	46
	References	46
Chapter 3	Membranes for the Removal of Endocrine Disrupting Compounds from Aqueous Environments	52
	<i>Khairul Anwar Mohamad Said, Clara Sari and Md Rezaur Rahman</i>	
3.1	Introduction	52
3.2	Toxicity of EDC	53
3.2.1	Source and Groups of EDCs	53
3.3	Conventional EDC Treatment Method	54
3.3.1	Physical Treatment	55
3.3.2	Chemical Treatment	57
3.3.3	Biological Treatment	58

3.4	Advanced EDC Removal Technologies	59
3.4.1	Adsorption-based Technologies	59
3.4.2	Membrane-based Technologies	60
3.4.3	Advanced Oxidation Processes	63
3.4.4	Photocatalytic Membrane Reactor	65
3.5	Conclusions	67
	List of Abbreviations	68
	Acknowledgements	68
	References	68
Chapter 4	Ultrafiltration for Laundry Wastewater Treatment	76
	<i>Nur Alyaa Syfina Zakaria, Pei Sean Goh, Woei Jye Lau and Ahmad Fauzi Ismail</i>	
4.1	Introduction	76
4.2	Laundry Wastewater	79
4.3	Treatment Technologies for Laundry Wastewater	81
4.4	Principle and UF Membrane Configuration	89
4.5	UF Membrane Materials	91
4.6	Challenges of UF	91
4.7	UF Membrane Modification	92
4.8	UF for Laundry Wastewater Treatment	95
4.9	Conclusion	101
	Acknowledgements	101
	References	101
Chapter 5	TiO₂-Graphitic Carbon Nitride-based Nanocomposites for the Degradation of Emerging Pollutants	115
	<i>Devagi Kanakaraju and Lim Ying Chin</i>	
5.1	Introduction	115
5.2	Titanium Dioxide	116
5.3	Crystalline Structures of Titanium Dioxide	116
5.4	Mechanism of TiO ₂ Photocatalysis	117
5.5	Limitations of TiO ₂	119
5.6	Strategies for Improving Limitations of TiO ₂	120
5.7	Graphitic Carbon Nitride	121
5.8	TiO ₂ -gC ₃ N ₄ -based Nanostructures: Synthesis Methods and Properties	123
5.8.1	Binary TiO ₂ -gC ₃ N ₄ Nanostructures	124
5.8.2	TiO ₂ -gC ₃ N ₄ -based Nanostructures	125
5.9	Applications of TiO ₂ -gC ₃ N ₄ -based Nanocomposites for Emerging Pollutant Removal	126
5.10	Conclusion	128
	References	128

Chapter 6 Carbon-based Nanomaterials for the Removal of Emerging Water Pollutants	133
<i>Wan Hazman Danial, Nurasyikin Hamzah, Mohamad Wafiuddin Ismail, Nurul Iman Aminudin, Saiful Arifin Shafiee and Anwar Iqbal</i>	
6.1 Introduction	133
6.2 Carbon-based Nanomaterials for the Removal of Emerging Water Pollutants	135
6.2.1 Activated Carbon Nanoparticles	135
6.2.2 Nanodiamonds	140
6.2.3 Fullerenes	145
6.2.4 Graphene and Graphene Oxides	153
6.2.5 Carbon and Graphene Quantum Dots	156
6.2.6 Carbon Nanotubes and Nanofibers	160
6.2.7 Carbon Aerogels	168
6.3 Conclusion	171
6.4 Future Prospects	172
References	172
Chapter 7 Synthesis and Functionalization of Metal Oxides for the Removal of Organic Pollutants	178
<i>Khalid Umar, Saima Khan Afridi and Anwar Iqbal</i>	
7.1 Introduction	178
7.2 Various Methods to Synthesize Metal Oxides for the Removal of Pollutants	180
7.2.1 Bottom Up Approach	180
7.2.2 Top-down Approach	190
7.3 Modification in Metal Oxides for Pollutant Removal	191
7.3.1 Doping of Metal-to-metal Oxides	192
7.3.2 Doping of Non-metal-to-metal Oxides	192
7.3.3 Doping of Polymers to Metal Oxides	194
7.4 Photocatalytic Degradation of Organic Pollutants Using Metal Oxides	196
7.4.1 Photocatalytic Degradation of Pesticides Using Metal Oxides	196
7.4.2 Photodegradation of Dyes Using Metal Oxides	197
7.4.3 Photodegradation of Drugs Using Metal Oxides	197
7.5 Conclusion	199
Acknowledgments	200
References	200

Chapter 8 Application of Nanoparticles in the Mitigation of Harmful Algal Blooms	208
<i>A. Iqbal, D. H. Y. Yanto, N. Mohammad-Noor, H. Thoha, M. W. Ismail, N. H. H. Abu Bakar, M. R. Roziawati, S. Abu-Romman and M. A. Sweiss</i>	
8.1 Introduction	208
8.2 Harmful Algal Bloom Definition and Challenges	209
8.3 Occurrences of HABs in Various Regions	209
8.4 Strategic Management of HABs	210
8.5 Nanoparticles	210
8.6 Basic Concept of Mitigating HABs Using Nanoparticles	211
8.6.1 Physical Method by Adsorption	211
8.6.2 Photocatalysis	215
8.7 Conclusions	219
Acknowledgements	219
References	220
Subject Index	223

Membranes for the Removal of Endocrine Disrupting Compounds from Aqueous Environments

KHAIRUL ANWAR MOHAMAD SAID^{a,b,c,*}, CLARA SARI^a AND MD REZAUR RAHMAN^{a,c}

^aDepartment of Chemical Engineering and Energy Sustainability, Faculty of Engineering, Universiti Malaysia Sarawak (UNIMAS), Malaysia; ^bAdvanced Membrane and Material Research Unit (AMMRU), Faculty of Engineering, Universiti Malaysia Sarawak (UNIMAS), Malaysia; ^cUNIMAS Water Centre, Faculty of Engineering, Universiti Malaysia Sarawak (UNIMAS), Malaysia
E-mail: mskanwar@unimas.my

3.1 Introduction

Endocrine-disrupting chemicals or compounds (EDC) are varied arrays of compounds that can disrupt the typical operation of the endocrine system, which controls the production and regulation of hormones in the body.¹ These compounds have the ability to imitate, obstruct, or disrupt the function of natural hormones, resulting in various negative impacts on human health and the environment.² EDCs encompass a range of chemical categories, including pharmaceuticals, pesticides, substances utilized in the plastics sector and consumer goods, industrial waste items, contaminants, and

certain naturally occurring plant components.³ EDCs encompass both natural molecules like phytoestrogens and manufactured chemicals such as pesticides, plastics, and medications.

The common technique employed to eliminate chemical pollutants from drinking water treatment systems is not highly efficient. Research has shown that flocculation or coagulation processes are able to remove less than 40% of EDC.⁴ UV irradiation, ozonation, and membrane treatment are advanced methods that can enhance water purification by eliminating EDCs.⁵ Compared to other advanced technologies that may discharge treatment by-products into the water, membranes are highly effective at reducing the concentration of EDCs.⁶ Membrane techniques such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) are commonly used in water treatment facilities.⁷

3.2 Toxicity of EDC

3.2.1 Source and Groups of EDCs

EDCs, according to the description by the US Environmental Protection Agency can be categorized as a substance that is not produced by an organism with the ability to manipulate the hormone metabolism.⁸ The mechanism by which EDCs disrupt hormones starts by them mimicking the hormone structure that allows them to bind the receptor. The binding of EDCs to the receptor blocks the actual hormone thus leading to instability especially to the organisms endocrine, immune, and nervous systems.⁹ The disruption in the vital function could cause several diseases mainly cancer, diabetes, and infertility.¹⁰ As well as diseases, EDCs may contribute to genetic changes by modifying the DNA through acetylation and methylation which could still occur even at low concentrations.¹¹ A verbatim description by the World Health Organization (WHO) regarding endocrine disrupting compounds is: “group of exogenous compounds that interfere with endocrine system functioning and has adverse health effects on organ-ism and its subpopulation/progeny”.¹²

Another name for EDCs is endocrine modulator and environmental hormone which can be categorized as either natural or synthetic depending on the synthesis pathways. Some of the synthetic endocrine modulators are bisphenol A, polychlorinated biphenyls, and triclosan while the natural source is phytoestrogen which can be found in soy milk. Meanwhile, the EDCs that are responsible for interfering with estrogen hormone are xenoestrogen which can be sourced from bisphenol A and soy milk. Both EDCs are known to mimic the estrogen hormone which allow it to bind to the hormone receptor that control the reproductive system. The binding of EDCs to the receptor in the case of xenoestrogen will induce irregular development, DNA modification, and the alteration of the placenta.¹³ In the US, based on population sampling from urine analysis, it is approximated that 92% of