Ferhan Çeçen and Özgür Aktaş

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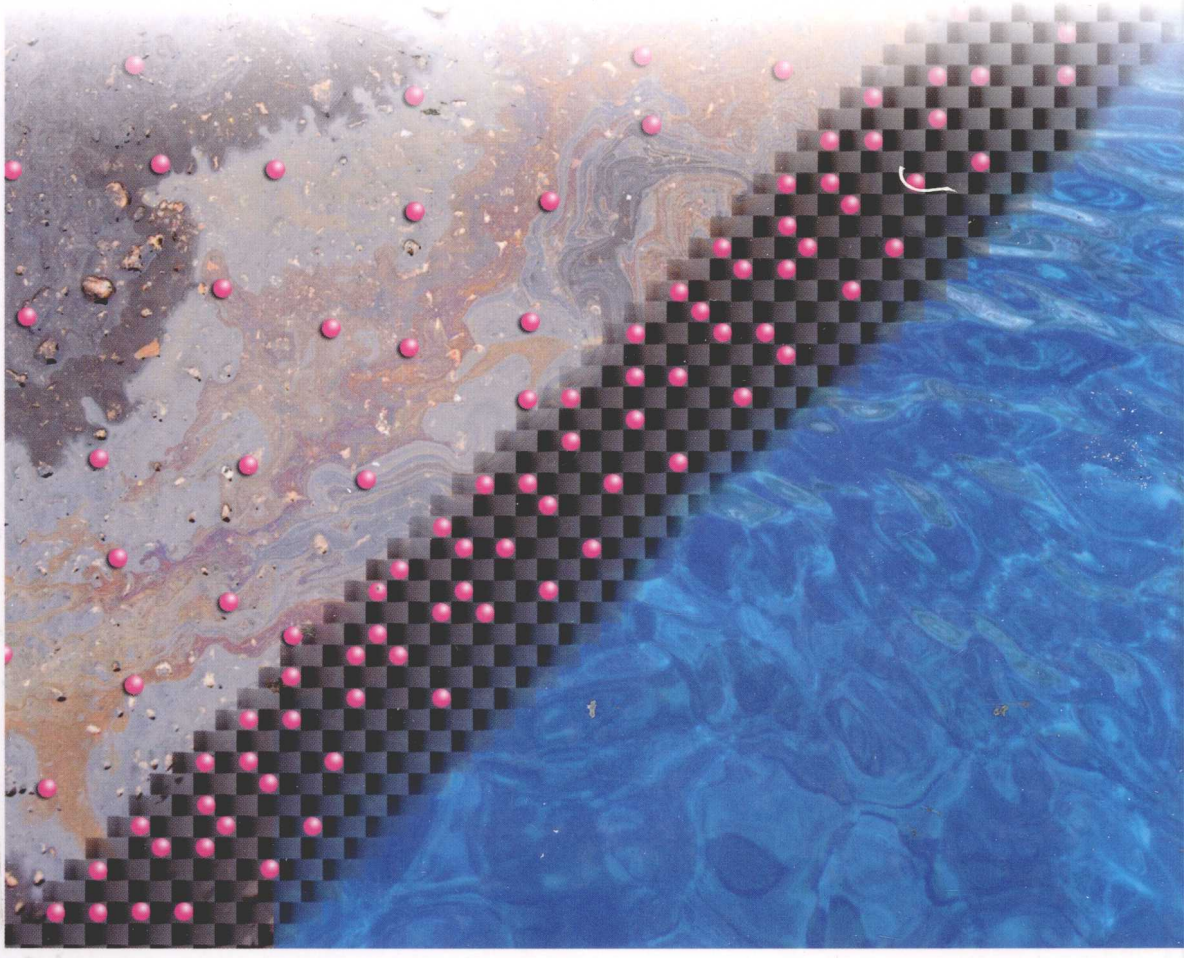
Activated Carbon for Water and Wastewater Treatment

Integration of Adsorption and Biological Treatment



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The Authors

Prof. Ferhan Çeçen
Bogazici University
Inst. of Environmental Sciences
34342 Istanbul
Turkey

Dr. Özgür Aktaş
TUBITAK-MRC
Environment Institute
41470 Gebze, Kocaeli
Turkey

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Preface

Purpose of the Book

The subject of the book is the 'integrated application of activated carbon adsorption with biological processes in water and wastewater treatment.' The enhancement of biological mechanisms by activated carbon adsorption merits serious study since it has been shown to be an effective method for the elimination of various organic and inorganic environmental pollutants.

During my studies over many years on adsorption and biodegradation, alone or together with my students, I realized with some surprise that the existing books on these subjects were either addressing activated carbon adsorption or biological treatment, but not both together in an integrated manner. I also realized that few books contained single chapters that dealt with either PACT or BAC processes. While invaluable work had been published in the form of papers or chapters, all these addressed some specific aspect of integrated treatment, and there was no comprehensive book that gave a detailed account of the different aspects of integrated adsorption and biological treatment. Thus, my idea to write this book originated from my own needs, and the idea was then supported by the book's co-author, Özgür Aktaş. Our goal in writing the book is to provide the reader with a document that attempts to present in a unified way most of the material to date on this subject.

The project necessitated an extensive literature survey spanning a period of approximately 40 years, from the beginning of integrated treatment in the 1970s to the present day. As a result, the book was inevitably expanded to include a wide range of topics. It covers the positioning of various integrated adsorption and biological removal treatment systems within the water and wastewater treatment train, describes how various pollutants can be removed, highlights the mechanisms that underlie the improved performance in small- and full-scale integrated systems, and extensively discusses to what extent pollutants can be eliminated from water or wastewater and what other side advantages are to be expected. However, for a full understanding, only to look at the underlying mechanisms and extent of removal would be inadequate. Therefore, we have also attempted to describe and analyze suspended- or attached-growth reactors involving PAC or GAC in mathematical terms. In this context, models pertaining to integrated water

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and wastewater treatment systems are also discussed. Results from small- and full-scale water and wastewater treatment are best understood if mechanisms and mathematical analyses of integrated adsorption and biological treatment systems are considered jointly.

In preparing this book, the assumption was made that the reader is equipped with basic knowledge of environmental science and technology, particularly the basics of adsorption and biological treatment. Thus, the book is not an elementary textbook, but is intended for people who are already involved with adsorption and/or biological processes. The principal readership of this book will be in the academic community, to whom the book will hopefully be useful. Some parts of the book may also be used for teaching of graduate level courses in environmental and chemical engineering.

The hope is that the book will appeal to people from both science and engineering disciplines. For scientists, who generally deal with fundamentals, it may be of interest to see the true value of integrated processes in practice. To practicing people, such as engineers operating water or wastewater treatment plants, who are mostly concerned with results, the book should provide a fundamental understanding of the main mechanisms in integrated adsorption and biotreatment. It should also serve as a work of reference for all those engaged in institutions relating to water quality, activated carbon production, and activated carbon adsorption.

Organization of the Book

Chapter 1 provides a brief overview of the history of activated carbon and its use in the water and wastewater treatment sector, and also gives a brief introduction to integrated adsorption and biological treatment.

Chapter 2 is an introductory chapter covering the fundamentals of adsorption and adsorption systems used in water and wastewater treatment. Since the basics of adsorption and adsorber systems are well explained in the existing literature, the chapter focuses on the main aspects of adsorbers that are also integrated into biological systems.

Chapters 3–7 are mainly devoted to the integration of activated carbon adsorption with biological processes in wastewater treatment.

Chapter 3 addresses the integration of activated carbon in biological wastewater treatment. It first highlights the progression from adsorption to concurrent adsorption and biological removal in wastewater treatment. The basic idea in this chapter is to give a clear idea of the main mechanisms underlying the observed positive effects in integrated systems. After this, the improvement of organics removal, removal of volatile pollutants, nitrification, denitrification, and anaerobic digestion in integrated systems are discussed. The chapter also includes the impact of activated carbon on biological sludge. Following the basic mechanisms, two basic processes are discussed that currently integrate the merits of activated carbon adsorption and biological removal in a single unit: the suspended-growth PACT process and the attached-growth biological activated carbon (BAC) process.

Another specific application, the coupling of membrane bioreactors (MBRs) with activated carbon, is also considered.

Chapter 4 concentrates on the effect of activated carbon in biological removal of pollutants. This chapter focuses on the removal of specific compounds as well as the extent of pollutant reduction in various types of wastewater, such as industrial wastewaters and landfill leachates, which contain many inhibitory, toxic, slowly degradable or nonbiodegradable pollutants.

Complementary to **Chapter** 4, which discusses the results and experiences from laboratory- and pilot-scale studies, **Chapter** 5 provides examples of full-scale PACT and BAC applications in wastewater treatment.

Chapter 6 addresses the modeling of combined adsorption and biological wastewater treatment systems. Relevant background information on mass transport, biodegradation, and adsorption processes is discussed in order to throw light on the complex interactions between adsorption and biological removal. The chapter then looks at the basic models that have been developed for attached-growth (BAC) and suspended-growth (PACT) systems.

Chapter 7 deals with bioregeneration of activated carbon, a very important phenomenon in all integrated systems. Bioregeneration is defined as the renewal of the adsorptive capacity of activated carbon by microorganisms in order to provide further adsorption. This chapter provides a comprehensive analysis of various aspects of GAC and PAC bioregeneration and the models describing bioregeneration.

The second part of the book, extending from **Chapter** 8 to 11, focuses on issues related specifically to drinking water treatment and addresses the integration of activated carbon adsorption with biological removal in this field.

Chapter 8 addresses the rationale for the introduction of biological processes into water treatment in general, highlighting the development and role of Biological Activated Carbon (BAC) Filtration. The significance of Natural Organic Matter (NOM) in drinking water treatment is discussed. This chapter also includes detailed information about the importance of ozonation, a treatment step that often precedes BAC filtration. The adsorption and biodegradation potential of raw and ozonated waters are discussed, as these properties have a strong influence on subsequent BAC filtration.

Chapter 9 deals with the removal of NOM, nutrients, and various organic and inorganic micropollutants in BAC filtration. Both removal mechanisms and the extent of removal are discussed. The chapter also includes a section on the characteristics and determination of biomass in BAC filters and on the safety of finished water.

Chapter 10 addresses the full-scale application of BAC filtration of drinking water. The chapter first discusses the limits set for the re-growth potential of water. It covers experiences from different water treatment plants and exemplifies the extent of the reduction of organic and inorganic pollutants that can be achieved.

Chapter 11 addresses the modeling of BAC filtration in drinking water treatment. Since the fundamentals of mass transport, biodegradation, and adsorption are discussed in **Chapter** 6, the only issues covered in this chapter are those pertaining specifically to drinking water treatment. The chapter provides an overview

of drinking water biofiltration models that have been developed to describe NOM and micropollutant removal.

Chapter 12 provides an overview of some of the issues discussed in the book, and highlights the need for further research on integrated adsorption and biological removal in water and wastewater treatment.

Suggestions for the Reader

In writing this book, the attempt was made to treat each chapter as a stand-alone topic while at the same time not impairing the cohesiveness of the whole subject. Therefore, in almost all chapters, frequent cross-referencing to other chapters is provided.

Bearing in mind that not all chapters are necessary for every reader, the following suggestions are made:

For a reader who wants to acquire a general idea about adsorption and its historical evolution in combination with biological processes in water and wastewater treatment, it may be sufficient to concentrate on **Chapter** 1.

Chapter 2 presents the fundamentals of adsorption and the use of adsorbers in the water/wastewater field. It can be read independently of other chapters and is perfectly suited to a reader who is interested in adsorption only, and not in biological processes.

Chapter 3 is the key to the comprehension of the chapters that follow, and the reader who wishes to gain a fundamental understanding of the mechanisms and synergism associated with integrated adsorption and biological removal is strongly advised to study it.

The reader who is only interested in wastewater treatment and wants to focus on operational and practical aspects of integrated adsorption and biological removal needs to read **Chapters** 2, 3, 4 and 5 only.

To acquire further insight into the mechanism and mathematical description of integrated adsorption and biological removal, the reader is advised to refer also to **Chapters** 6 and 7, which address modeling of integrated systems and bioregeneration of activated carbon, respectively.

In general, the reader who is interested in the combination of activated carbon adsorption with biological processes in drinking water treatment should refer to **Chapters** 8 to 11. For this reader it would also be helpful to read **Chapter** 3 first. **Chapter** 8 provides general information on BAC filtration in drinking water treatment, and detailed information on this subject is provided in **Chapter** 9. The reader who is interested in practical aspects of BAC filtration and wants to learn about possible full-scale applications of the process should refer to **Chapter** 10, while the reader who is interested in the mathematical formulation of BAC filtration of drinking water is advised to examine the models presented in **Chapter** 11, but, before this, it would be most useful to read **Chapter** 6.

Ferhan Çeçen

List of Abbreviations

16S rDNA	Small Sub-Unit (SSU) rDNA
16S rRNA	Small Sub-Unit (SSU) rRNA
2,4-D	2,4-Dichlorophenoxyacetate
2-FB	2-Fluorobenzoate
5-Fu	5-Fluorouracil
ABS	Acrylonitrile Butadiene Styrene
AC	Activated Carbon
AFLP	Amplified Fragment Length Polymorphism
AMO	Ammonia Monooxygenase
amoA	Ammonia Monooxygenase gene
AOB	Ammonia Oxidizing Bacteria
AOC	Assimilable Organic Carbon
AOCl	Adsorbable Organic Chlorine
AOP	Advanced Oxidation Process
AOX	Adsorbable Organic Xenobiotics (Halogens)
APHA	American Public Health Association
AS	Activated Sludge
ASTM	American Society for Testing and Materials
ATP	Adenosine Triphosphate
B(GAC)	Biological Granular Activated Carbon
BAC	Biological(ly) Activated Carbon (used primarily for granular activated carbon)
BAC-FBR	Fluidized-Bed Reactor containing biological GAC (BAC)
BAF	Biological Aerated Filter
BASM	Biodegradation/Adsorption–Screening Model
BDOC	Biodegradable Dissolved Organic Carbon
BET	Brunauer, Emmett, Teller
BFAC	BioFilm on Activated Carbon (Model)
Bi	Biot Number
BioMAC	Biological Membrane Assisted Carbon Filtration
BKME	Bleached Kraft Pulp Mill Effluent
BOD	Biochemical Oxygen Demand
BOM	Biodegradable Organic Matter

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BP	Bromophenol
BPA	Bisphenol A
BSF	Biological Rapid Sand Filtration
BTEX	Benzene, Toluene, Ethylbenzene, Xylene
BTX	Benzene, Toluene, Xylene
BV	Bed Volume
CAA	Chloroacetaldehyde
CB	Chlorobenzene
CBZ	Carbamazepine
CF	Continuous-Flow
CMF	Continuous Microfiltration
CMF-S	Continuous Microfiltration-Submerged
COD	Chemical Oxygen Demand
CP	Chlorophenol
CSTR	Continuous-flow Stirred Tank Reactor
CUR	Carbon Usage Rate
Cytr	Cytarabine
Da	Damköhler Number
DAF	Dissolved Air Flotation
DBP	Disinfection By-Product
DCA	Dichloroethane
DCE	Dichloroethene
DCF	Diclofenac
DCM	Dichloromethane
DCP	Dichlorophenol
D_g	Solute Distribution Parameter
DNP	Dinitrophenol
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
DOM	Dissolved Organic Matter
DTPA	Diethylene Triamine Pentaacetic Acid
DZP	Diazepam
E2	17 β-Estradiol
E3	Estriol
EBCT	Empty-Bed Contact Time
EC	Expanded Clay
EDC	Endocrine Disrupting Compound
EDTA	Ethylene Diamine Tetraacetic Acid
EE2	17 α-Ethinylestradiol
EEM	Excitation-Emission Matrix
EOCl	Extractable Organic Chlorine
EPS	Extracellular Polymeric Substances
ESEM	Environmental Scanning Electron Microscopy
F/M	Food to Microorganism (ratio)
FA	Free Ammonia

FBR	Fluidized-Bed Reactor
FNA	Free Nitrous Acid
GAC	Granular Activated Carbon
GAC/BAC	Granular /Biological Activated Carbon (with no clear distinction)
GAC-FBR	Fluidized-Bed Reactor packed with Granular Activated Carbon
GAC-MBR	GAC added Membrane Bioreactor
GAC-SBBR	GAC Reactor operated as a Sequencing Batch Biofilm Reactor
GAC-UASB	Upflow Anaerobic Sludge Blanket packed with Granular Activated Carbon
GAC-UFBR	Upflow Fixed-Bed Reactors packed with GAC
GC-MS	Gas Chromatography-Mass Spectrometry
HAA	Haloacetic Acid
HAA5	Five Haloacetic Acids
HAAFP	HAA Formation Potential
HLR	Hydraulic Loading Rate
HMW	High Molecular Weight
HMX	High Melting eXplosive
HPC	Heterotrophic Plate Count
HRT	Hydraulic Retention Time
HSDM	Homogeneous Surface Diffusion Model
IAS	Ideal Adsorbed Solution
IAST	Ideal Adsorbed Solution Theory
IBP	Ibuprofen
IBPCT	Integrated Biological-Physicochemical Treatment
IC_{50}	Concentration leading to 50% inhibition in biological tests
ISIAS	Improved Simplified Ideal Adsorbed Solution
IUPAC	International Union of Pure and Applied Chemistry
KATOX	A process leading to accelerated oxidation in the presence of activated carbon
LC_{50}	Concentration leading to lethal effect in 50% of biological species
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LDF	Linear Driving Force
LMW	Low Molecular Weight
MADAM	Michigan Adsorption Design and Applications Model
MAP	Microbially Available Phosphorus
MBR	Membrane BioReactor
MDBA	Multiple-Component Biofilm Diffusion Biodegradation and Adsorption model
MEP	Metabolic End Products
MF	Microfiltration
MIB	2-Methylisoborneol
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed Liquor Volatile Suspended Solids
MNP	*m*-Nitrophenol

MTBE	Methyl-Tert-Butylether
MTZ	Mass Transfer Zone
MW	Molecular Weight
NBDOC	Nonbiodegradable Dissolved Organic Carbon
NMR	Nuclear Magnetic Resonance
NOB	Nitrite Oxidizing Bacteria
NOM	Natural Organic Matter
NP	Nitrophenol
NPDES	National Pollutant Discharge Elimination System
NPEs	Nonylphenol Ethoxylates
NPX	Naproxen
OCD	Organic Carbon Detection
OCPSF	Organic Chemicals, Plastics and Synthetic Fiber
OND	Organic Nitrogen Detection
OUR	Oxygen Uptake Rate
PAC	Powdered Activated Carbon
PAC-MBR	PAC added Membrane Bioreactor
PACT	Powdered Activated Carbon Treatment
PACT®	Registered Powdered Activated Carbon Treatment
PAE	Phthalate Ester
PAH	Polycyclic Aromatic Hydrocarbon
PBR	Packed-Bed Reactor
PCE	Perchloroethylene (Tetrachloroethylene)
PCP	Pentachlorophenol
PCPs	Personal Care Products
PCR	Polymerase Chain Reaction
PDM	Pore Diffusion Model
Pe	Peclet number
PFR	Plug Flow Reactor
PNP	*p*-Nitrophenol
POC	Particulate Organic Carbon
POP	Persistent Organic Pollutant
POTW	Publicly Owned Treatment Works
PPCPs	Pharmaceutical and Personal Care Products
PZG	Plane of Zero Gradient
RBF	River Bank Filtration
RDX	Royal Demolition eXplosive
RFB	Recycle Fluidized-Bed
RWW	Rheinisch-Westfälische Wasserwerksgesellschaft
SAT	Soil Aquifer Treatment
SBBR	Sequencing Batch Biofilm Reactor
SBR	Sequencing Batch Reactor
SBR-PACT	Powdered Activated Carbon Treatment in a Sequencing Batch Reactor
SCFB	Semi-Continuously Fed Batch (Reactor)

SCOD	Soluble Chemical Oxygen Demand
SCR	Specific Cake Resistance
SEC	Size Exclusion Chromatography
SEM	Scanning Electron Microscopy
Sh	Sherwood number
SIAS	Simplified Ideal Adsorbed Solution
SMP	Soluble Microbial Products
SOC	Synthetic Organic Compound
SOUR	Specific Oxygen Uptake Rate
SRF	Specific Resistance to Filtration.
SRT	Sludge Retention Time
SS	Suspended Solids
SSF	Slow Sand Filtration
St	Stanton number
STP	Sewage Treatment Plant
SUVA	Specific Ultraviolet Absorbance
SVI	Sludge Volume Index
SVOC	Semi-Volatile Organic Compound
TCA	Trichloroethane
TCB	Trichlorobenzene
TCE	Trichloroethylene
TCOD	Total Chemical Oxygen Demand
TDS	Total Dissolved Solid
THM	Trihalomethane
THMFP	Trihalomethane Formation Potential
TKN	Total Kjeldahl Nitrogen
TMP	Transmembrane Pressure
TN	Total Nitrogen
TOC	Total Organic Carbon
T-RFLP	Terminal-Restriction Fragment Length Polymorphism
TSMSBM	Transient-State Multiple-Species Biofilm Model
TSS	Total Suspended Solids
TTHM	Total Trihalomethanes
TVH	Total Volatile Hydrocarbons
UASB	Upflow Anaerobic Sludge Blanket
UF	Ultrafiltration
USEPA	United States Environmental Protection Agency
UV	Ultraviolet
VOC	Volatile Organic Compound (Carbon)
WAO	Wet Air Oxidation
WAR	Wet Air Regeneration
WWTP	Wastewater Treatment Plant
XOC	Xenobiotic Organic Compound

Acknowledgement

This work would not have been possible without the Bogaziçi University, Istanbul/Turkey, to which I owe much, first for my education and later for its support during my activities as a faculty member. Most of the information presented in this book was accumulated during the last 20 years of my teaching and research at the University, much of it supported through grants from the Research Fund. Similarly, I am indebted to our national research council TÜBİTAK for its support of several research projects in these years.

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I am grateful to all of my former thesis students with whom I had the opportunity to work, who helped me realize my ideas and contributed to many of the concepts and results presented in this book. Of these students, two in particular have done great work that has directly contributed to the book:

Özgür Aktaş, who is also the co-author of this book, worked mainly on wastewater treatment and produced his MSc thesis, under my supervision, on 'Powdered activated carbon addition to activated sludge in the treatment of landfill leachate.' After this, his PhD thesis, also under my supervision, 'Bioregeneration of activated carbon in the treatment of phenolic compounds,' contributed much to the literature.

Kozet Yapsakli, a PhD student, wrote her thesis on 'Application of biological activated carbon (BAC) in drinking water treatment' under my supervision. This study further extended our understanding of integrated adsorption and biological removal as applied to drinking water treatment. Some examples, described in Chapters 8 and 9 of this book, are derived from these studies. I also thank her for her careful reading of the chapters in this book, particularly those related to drinking water treatment.

Special thanks go to my research assistant Ayşe Gül Geyik who has worked tirelessly on literature surveys, drawing, and formatting.

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Finally, I am indebted to my family members, who supported me throughout my life in all aspects. I dedicate this book to my father, now deceased, who had a great influence on my personality and on my path to becoming an academician.

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