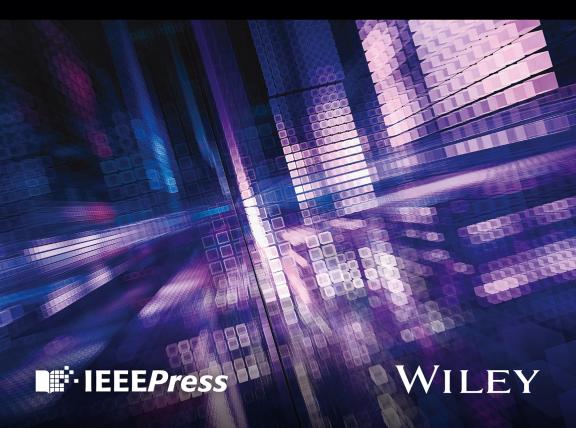
Carbon-based Nanomaterials for Green Applications

Edited by

Upendra Kumar • Piyush Kumar Sonkar Suman Lata Tripathi



Carbon-based Nanomaterials for Green Applications

IEEE Press 445 Hoes Lane Piscataway, NJ 08854

IEEE Press Editorial Board

Sarah Spurgeon, Editor-in-Chief

Moeness Amin Jón Atli Benediktsson Adam Drobot James Duncan Ekram Hossain Brian Johnson Hai Li James Lyke Joydeep Mitra Desineni Subbaram Naidu Tony Q. S. Quek Behzad Razavi Thomas Robertazzi Diomidis Spinellis

Carbon-based Nanomaterials for Green Applications

Edited by

Upendra Kumar Indian Institute of Information Technology Allahabad Prayagraj Uttar Pradesh India

Piyush Kumar Sonkar Department of Chemistry, MMV, Banaras Hindu University Varanasi, Uttar Pradesh India

Suman Lata Tripathi School of Electronics and Electrical Engineering Lovely Professional University Phagwara, Punjab India



Copyright © 2025 by The Institute of Electrical and Electronics Engineers, Inc. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey. Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at www.copyright. com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at http://www.wiley.com/go/permission.

The manufacturer's authorized representative according to the EU General Product Safety Regulation is Wiley-VCH GmbH, Boschstr. 12, 69469 Weinheim, Germany, e-mail: Product_Safety@wiley.com.

Trademarks: Wiley and the Wiley logo are trademarks or registered trademarks of John Wiley & Sons, Inc. and/or its affiliates in the United States and other countries and may not be used without written permission. All other trademarks are the property of their respective owners. John Wiley & Sons, Inc. is not associated with any product or vendor mentioned in this book.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Further, readers should be aware that websites listed in this work may have changed or disappeared between when this work was written and when it is read. Neither the publisher nor authors shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at www.wiley.com.

Library of Congress Cataloging-in-Publication Data Applied for:

Hardback ISBN: 9781394243396

Cover Design: Wiley

Cover Image: © Baac3nes/Getty Images

Set in 9.5/12.5pt STIXTwoText by Straive, Pondicherry, India

Dedicated to Our Authors, Collaborators, and the Family Members

Contents

2.1.1

2.1.2

2.1.3 2.1.4

About the Editors	xxv
List of Contributors	xxix
Preface xxxvii	
Acknowledgments	xxxix

Carbon Nanotubes 21

Graphene 22 Graphene Oxide 22

Fullerenes 22

1	Green Energy: An Introduction, Present, and Future Prospective 1
	Manoj Singh Adhikari, Raju Patel, Manoj Sindhwani, and Shippu Sachdeva
1.1	Introduction 1
1.2	Present Status of Green Energy 3
1.3	Global Renewable Energy Capacity 4
1.4	Leading Green Energy Technologies 5
1.5	Challenges in Green Energy Adoption 7
1.6	Prospects of Green Energy 8
1.7	Sustainable Practices in Green Energy 10
1.8	Case Studies of Successful Green Energy Projects 12
1.9	Policy and Regulatory Framework for Green Energy 13
1.10	Opportunities and Challenges in the Evolution to a Green Energy
	Future 14
1.10.1	Opportunities 14
1.10.2	Challenges 16
1.11	Conclusion 16
	References 17
2	Properties of Carbon-Based Nanomaterials and Techniques
	for Characterization 21
	Ravi Tejasvi
2.1	Introduction 21

2.2	Significance in Green Energy 22
2.2.1	Energy Storage 23
2.2.2	Solar Energy 23
2.2.3	Catalysis and Fuel Cells 23
2.2.4	Thermal Management 23
2.2.5	Environmental Remediation 23
2.3	Techniques for Characterization of Properties of Carbon
	Nanomaterials 24
2.3.1	Electrical Conductivity 25
2.3.2	Thermal Conductivity 28
2.3.3	Mechanical Strength 29
2.3.4	Surface Area Characterization 30
2.3.5	Scanning Electron Microscopy 32
2.3.6	Energy Dispersive X-ray Spectroscopy 33
2.3.7	Transmission Electron Microscopy 34
2.3.8	Electron Energy Loss Spectroscopy 37
2.3.9	Atomic Force Microscopy 38
2.3.10	Raman Spectroscopy 39
2.3.11	Photoluminescence 40
2.3.12	Time-Resolved Photoluminescence 41
2.3.13	Thermal Gravimetric Analysis and Differential Scanning Calorimetry 42
2.3.14	Fourier Transform Infrared Spectroscopy 43
2.3.15	UV-Vis-NIR Spectroscopy 44
2.3.16	X-ray Photoelectron Spectroscopy 45
2.3.17	Small Angle X-ray Scattering 47
2.3.18	X-ray Diffraction Analysis 48
2.3.19	Scanning Electrochemical Microscopy 49
2.3.20	Electrochemical Impedance Spectroscopy 50
2.4	Conclusion 51
	References 52
7	Cross Energy Droppet and Enture Droppetings 57
3	Green Energy: Present and Future Prospectives 57 Irtiga Amin, Quraazah Akeemu Amin, and Harpreet Kaur
2 1	Introduction 57
3.1 3.1.1	
3.2	Systematic Review Survey Reports 59 Sustainable Energy Resources 62
3.2.1	Wind Energy 63
3.2.1.1	Applications of Wind Turbine Systems 65
3.2.1.1	Advantages of Wind Energy 67
3.2.1.2	Disadvantages of Wind Energy 68
3.2.1.3	Future Prospectives and Challenges 69

3.2.2	Solar Energy 70
3.2.2.1	Applications of Solar Energy 71
3.2.2.2	Advantages of Solar Energy 72
3.2.2.3	Disadvantages of Solar Energy 73
3.2.2.4	Future Prospectives and Challenges 74
3.2.3	Biomass 75
3.2.3.1	Applications of Biomass 75
3.2.3.2	Benefits and Disadvantages of Biomass 78
3.2.3.3	Future Prospectives and Challenges 79
3.2.4	Geothermal Energy 80
3.2.4.1	Applications and Future Prospectives 81
3.2.5	Hydropower 82
3.2.6	Tidal and Wave Energy 84
3.2.6.1	Tidal Power 84
3.2.6.2	Wave Power 84
3.2.6.3	Benefits of Tidal and Wave Energy Systems 86
3.2.6.4	Challenges of Tidal and Wave Energy Systems 86
3.3	Non-Sustainable Energy Resources 86
3.3.1	Fossil Fuels 86
3.3.2	Atomic Energy 87
3.4	Existing Green Energy Models 87
3.5	Conclusions 88
	References 92
4	Carbon-Based 2D Materials: Synthesis, Characterization,
	and Their Green Energy Applications 95
	Minakshi Sharma, Varsha Yadav, Prachi Diwakar,
	Chandra Mohan Singh Negi, and Parvez Ahmed Alvi
4.1	Introduction 95
4.2	Synthesis of Graphene and Its Derivatives 97
4.2.1	Graphene-Based 2D Materials 97
4.2.2	Graphene 99
4.2.3	Graphene Oxide 100
4.2.4	Reduced Graphene Oxide 102
4.2.5	Graphitic Carbon Nitride 102
4.2.5.1	g-CN-Thin Film 104
4.2.5.2	Graphitic Carbon Nitride (g-CN)-Powder Form 104
4.2.5.3	Thin Film of g-CN 104
4.3	Properties of g-CN 108
4.3.1	Morphologyical Properties 108
4.3.2	Band Gap 109

x	Contents		
		 _	

4.3.3	Other Properties 109
4.4	Applications of g-CN 109
4.4.1	g-CN Role in Organic Solar Cells 110
4.4.2	g-CN Role in Perovskite Solar Cells 110
4.4.3	g-CN Role in Dye-Sensitized Solar Cells 111
4.4.4	g-CN Role as a Photocatalyst 111
4.4.5	g-CN-Sensing Applications 112
4.4.6	g-CN Environmental Applications 112
4.5	Conclusion 113
	References 114
5	Exploring the Potential of Graphene in Sustainable Energy Solutions 119
	M. Karthik, S. Allirani, G. Ilakkiya, and R. Adharsh
5.1	Introduction 119
5.2	Usage of Graphene in Various Sectors 121
5.3	Implicit Operations of Graphene in the Renewable Energy Sector 125
5.3.1	Battery Technology 125
5.3.2	Touchscreen 127
5.3.3	Integrated Circuits 128
5.3.4	Flexible Memory 129
5.3.5	Solar Power Generation 130
5.3.6	Photovoltaic Cells 131
5.3.7	Solar Cells 131
5.3.8	Lithium-Ion Batteries 131
5.3.9	Supercapacitors 132
5.3.10	Graphene Transistors 133
5.3.11	Graphene Semiconductors 135
5.3.12	Graphene Sensors 136
5.4	Catalysis 137
5.5	Renewable Energies 137
5.6	Nanotechnology 138
5.7	Conclusion 138
	Bibliography 139
6	Fullerene for Green Hydrogen Energy Application 141
	Manish Kumar and Sunil Kumar
6.1	Introduction 141
6.2	Green Hydrogen Energy 143
6.3	Fullerene as a Hydrogen Storage Material 145
6.4	Size Effect of Fullerene and Hydrogen Storage Efficiency 145
6.5	Functionalized Fullerene, Chemical Structure, and Its Hydrogen
	Storage Performance 146

6.5.1	Boron 147
6.5.2	Phosphorene or Black Phosphorus 147
6.5.3	Hexagonal Boron Nitride 148
6.5.4	Silicene 149
6.5.5	Carbon Nanotubes 149
6.5.6	Graphene 151
6.5.7	Ferrocene 151
6.5.8	MoS_2 152
6.5.9	Organometallic Framework 153
6.6	Charged Fullerene as Hydrogen Storage System 155
6.7	Hydrogen Storage in Hydro- or Hydrogenated Fullerene 155
6.8	Conclusions and Future Outlook 156
	Acknowledgments 156
	References 157
7	Graphyne-Based Carbon Nanomaterials for Green Energy
	Applications 163
	Kulsum Hashmi, Mohammad Imran Ahmad, Saman Raza, Nidhi Mishra,
	Seema Joshi, and Tahmeena Khan
7.1	Introduction 163
7.1.1	Structural Aspects of Graphyne 164
7.2	Graphyne-Based Carbon Nanomaterials for Green Energy Applications 166
7.2.1	Mechanisms Involved in Growth, Doping, Energy Storage,
	and Conversion Involving Graphyne 167
7.3	Fuel Cells 169
7.3.1	Oxygen Reduction Reaction (ORR) Catalyst for Hydrogen Fuel Cells or
	Metal-Air Batteries (MABs) 171
7.3.2	Lithium-Ion and Lithium-Metal Batteries 172
7.3.3	Supercapacitors 174
7.3.4	Wind Energy 176
7.4	Solar Energy 177
7.5	Wastewater Treatment 181
7.6	Perspectives and Conclusion 185
	Acknowledgments 185
	References 185
8	Mesoporous Carbon for Green Energy Applications 199
	Vikas Jangra, Narvadeswar Kumar, Harpreet Kaur, Lal Bahadur Prasad,
	and Piyush Kumar Sonkar
8.1	Introduction 199
8.2	Recent Advances in Synthetic Techniques 202
8.2.1	Hard Template Technique 203

8.2.1.1	Carbon Precursors 203
8.2.2	Soft Template Technique 204
8.3	Applications of Mesoporous Carbon 205
8.3.1	Applications in Lithium Batteries 205
8.3.2	Applications in Supercapacitors 210
8.3.3	Applications in Fuel Cells 213
8.4	Further Directions, Opportunities, and Challenges 217
8.5	Conclusions 218
	References 218
9	Green Synthesis of Carbon Dots and Its Application in Hydroger
	Generation Through Water Splitting 225
0.1	Mandakini Gupta
9.1	Introduction 225
9.2	Carbon Dots 227
9.3	Processes Used for Synthesis of CDs 228
9.3.1	Bottom-Up Synthesis Processes 229
9.3.1.1	Solvothermal/Hydrothermal Method 230
9.3.1.2	Sol-Gel Method 230
9.3.1.3	Microwave Irradiation 230
9.3.1.4	Carbonization Route 231
9.3.2	Top-Down Synthesis Processes 231
9.3.2.1	Laser Ablation 231
9.3.2.2	Arc Discharge 232
9.3.2.3	Chemical and Electrochemical Oxidation Methods 232 Ultrasonic Treatment 233
9.3.2.4	
9.4 9.4.1	Green Synthesis of Carbon Dots 234 Biomass-Based Green Synthesis of CDs 234
9.4.1.1	Biomass-Based Green Synthesis of CDs 234 Plant Waste-Based Green Synthesis of Carbon Dots 235
9.4.1.2	Animal Waste-Based Green Synthesis of CDs 236
9.4.1.2	Application of CDs in Water Splitting 237
9.5.1	Hydrogen Generation via Water Splitting (Photoreduction) 237
9.5.2	Photocatalytic Degradation of Organic Pollutants 241
9.6	Factors Affecting Characteristics of Nanomaterials of Carbon in
9. 0	Photocatalytic H ₂ Production 242
9.6.1	Doping 242
9.6.2	Defects 242
9.6.3	Dimensions 243
9.7	Conclusion 243
2.1	References 244
	1010101000 211

10	Carbon-Based Nanomaterials in Energy Storage Devices:
	Solar Cells 255
	Seraj Ahmad, Manoj Kumar, Kahkashan Khatoon, Akram Ali,
	and Himanshu Arora
10.1	Introduction 255
10.2	Carbon Nanotubes 257
10.2.1	Synthesis Techniques Concerning Carbon Nanotubes 257
10.2.2	Carbon Nanotube Applications in Solar Cell Technology 257
10.2.2.1	Transparent Conductive Electrodes 258
10.2.2.2	Charge Transport Materials 258
10.2.2.3	Enhanced Electron Transport 258
10.2.2.4	Improved Charge Collection 258
10.2.2.5	Transparency and Flexibility 259
10.2.2.6	Lightweight and Flexible Design 259
10.2.2.7	Tunable Aspects of Optics 259
10.2.2.8	Durability and Longevity 259
10.2.2.9	Compatibility with Other Materials 259
10.2.2.10	Scalability 259
10.2.3	Recent Advancements and Challenges 260
10.2.3.1	Recent Advancements 260
10.2.3.2	Challenges 260
10.3	Graphene 261
10.3.1	Synthesis Techniques 262
10.3.2	Utilizing Graphene in Solar Cell Applications 262
10.3.2.1	Transparent Conductive Electrodes 262
10.3.2.2	Charge Transport Layers 263
10.3.2.3	Light-Harvesting Enhancements 263
10.3.3	Recent Advancements and Challenges 263
10.3.3.1	Recent Advancements 263
10.3.3.2	Challenges 264
10.4	Carbon Dots 265
10.4.1	Synthesis Techniques 265
10.4.2	Applications of Solar Cell Carbon Dots 266
10.4.2.1	Light Harvesting and Sensitization 266
10.4.2.2	Charge Separation and Transport of Electrons 266
10.4.2.3	Energy Storage and Electrochemical Applications 267
10.4.3	Recent Advancements and Challenges 267
10.4.3.1	Recent Advancements 267
10.4.3.2	Challenges 268
10.5	The Future of Carbon-Based Nanomaterials in Solar Cell
	Technology 269

xiv Contents	
---------------------	--

10.5.1	Enhanced Light Harvesting and Absorption 269
10.5.2	Improved Charge Transport and Collection 269
10.5.3	Enhanced Stability and Durability 269
10.5.4	Scalable Synthesis and Manufacturing 270
10.5.5	Integration with New Advances in Solar Cell Technology 270
10.5.6	Environmental Sustainability and Cost-Effectiveness 270
10.6	Conclusion 270
	References 271
11	Carbon-Based Nanomaterials in Energy Storage Devices: Fuel Cells
	and Biofuel Cells 275
	Ponnusamy Thillai Arasu, Arumugam Murugan, G. Kanthimathi,
	A. Malar Retna, S. Daphne Rebekal, Natarajan Raman,
	Robin Kumar Samuel, and Tola Jebssa Masho
11.1	Introduction 275
11.2	Carbon-Based Nanomaterials' Function in Energy Storage 277
11.3	Carbon Nanotube-Based Materials for Use in Batteries 277
11.4	Carbon Nanotube Varieties 278
11.4.1	Single-Walled Carbon Nanotubes (SWCNTs) 279
11.4.2	Multi-Walled Carbon Nanotubes (MWCNTs) 279
11.4.2.1	Chirality 279
11.5	Carbon Nanoparticles 281
11.5.1	Supercapacitors 281
11.5.2	Batteries 281
11.5.3	Fuel Cells 282
11.5.4	Hybrid Energy Storage Systems 282
11.5.5	Quantum Dots 283
11.6	Carbon Nanosheets 284
11.7	Biofuels 285
11.7.1	Biofuel Classification 285
11.7.1.1	<u> </u>
11.7.2	Background of Biofuel 286
11.8	Morphological and Evolutionary Characteristics of Enzyme-Based
	Biofuels 287
11.8.1	Mediated Electron Transfer 287
11.8.1.1	NAD ⁺ -Dependent Enzymes 288
11.8.2	Direct Electron Transfer 289
11.9	Immobilization of Enzymes 290
11.9.1	Adsorption/Carrier-Binding Method 291
11.9.2	Covalent Bonding 293
11.9.3	Affinity Immobilization 294
11.9.4	Entanglement 294
11.9.5	Ionic Binding 295

11.9.6	Immobilization Associated with Metals 295				
11.10	Graphene and CNT Applications in Fuel Cells 296				
11.10.1	Comparative Performance Analysis of Existing Fuel Cell 296				
11.11	Conclusion 298				
11.12	Expected Future Application of Fuel Cells and Biofuel Cells 298				
11.13	Future Applications 298				
	References 299				
12	Carbon-Based Nanomaterials in Energy Storage Devices:				
	Supercapacitors 307				
	Shikha Chander, Veerabathuni Jaya Usha Praveena, and Meenu Mangal				
12.1	Introduction 307				
12.1.1	Graphene Supercapacitors as Energy Storage Devices 308				
12.2	Carbon Nanotube 311				
12.2.1	Functioning of the CNT Detectors 314				
12.3	Functionalization of Carbon Nanotubes 316				
12.3.1	Applications of Functionalized CNTs 317				
12.3.2	Precursor Features 318				
12.4	Reduced Graphene Oxide (rGO) Synthesis 318				
12.4.1	Synthesis of rGO-FCNT Hybrid 319				
12.5	Characterization 319				
12.5.1	Preparation of Electrodes and Cells 320				
12.5.2	Input Parameters for Analysis 320				
12.6	Results and Discussion 321				
12.6.1	Raman Analysis 321				
12.6.2	Powder X-Ray Diffraction (XRD) 322				
12.6.3	FTIR Analysis 323				
12.6.4	Scanning Electron Microscopy Analysis 324				
12.6.5	Transmission Electron Microscopy Analysis 325				
12.7	Applied Electrochemistry 326				
12.7.1	Galvanostatic Charge Discharge 326				
12.7.2	Electrochemical Impedance Spectroscopy (EIS) 327				
12.8	Conclusions 328				
12.9	Future Scope 328				
	References 328				
13	A Review of Effective Biomass, Chemical, Recycling and Storage				
	Processes for Electrical Energy Generations 331				
	Suman Lata Tripathi, Krishan Arora, and Celestine Lwendi				
13.1	Introduction 331				
13.2	Bio-Raw Materials and Utility 333				
13.3	Biomass Energy Conversion Techniques 334				
13.3.1	Thermochemical Conversion 336				
13.3.1.1	Combustion 336				

13.3.1.2	Biomass Pyrolysis 336
13.3.1.3	Gasification 337
13.3.2	Chemicval Conversion 337
13.3.2.1	Transesterification 338
13.3.3	Biochemical Conversion 338
13.3.3.1	Anaerobic Digestion 339
13.3.3.2	Fermentation 339
13.3.4	Bioelectrochemical Conversion 340
13.3.4.1	Microbial Fuel Cells 341
13.3.4.2	Microbial Electrolysis Cells (MECs) 342
13.4	Application Areas of Biomass Energy 343
13.5	Comparative Analysis of Modern Biomass Energy Conversion
	Techniques 343
13.6	Optimization Techniques for Effective Biomass Conversion
	and Supply Chain Management 343
13.7	Government Policies and Marketing Strategies 345
13.8	Applications of Biomass Energy and Biomass Products 346
13.9	Conclusions 346
	References 347
14	Carbon-Based Nanomaterials for Pollutants' Treatment 355
	Gaganpreet and Y. Pathania
14.1	Introduction 355
14.2	Allotropic Forms of Carbonaceous Nanomaterials 357
14.3	Synergistic Approaches for Carbonaceous Materials 359
14.4	Role of Carbonaceous Materials in Environmental Remediation 362
14.4.1	Removal of Air Pollutants 362
14.4.2	Removal of Water Pollutants 363
14.4.3	Soil Remediation 367
14.5	Environmental Impact of Carbon-Based Nanomaterials 368
14.6	Conclusions: Technological Challenges and Future Prospects 369
	Conflicts of Interest 370
	Authors' Contributions 370
	References 370
15	Carbon Nanomaterials for Detection and Degradation of Wastewater
	Inorganic Pollutants: Present Status and Future Prospects 383
	Prem Rajak, Ruchika Agarwal, Sohini Goswami, Satadal Adhikary,
	Suchandra Bhattacharya, Abhratanu Ganguly, and Sayantani Nanda
15.1	Introduction 383
15.2	Properties of Carbon Nanomaterials 387

15.3	Common Types of Carbon Nanomaterials 387			
15.3.1	Carbon Nanotubes 388			
15.3.2	Carbon Nanofibers 389			
15.3.3	Graphitic Carbon Nitride 390			
15.3.4	Activated Carbon 391			
15.3.5	Nanoporous Carbons 391			
15.3.6	Graphene in Wastewater Treatment 392			
15.4	Elimination of Inorganic Contaminants from Wastewater 393			
15.4.1	Adsorption 393			
15.4.2	Catalysis 394			
15.4.2.1	Photocatalysis 394			
15.4.2.2	Catalytic Wet Air Oxidation 396			
15.4.3	Antimicrobial and Antibiofouling Activities 397			
15.4.4	Desalination 399			
15.5	Carbon Nanomaterials for Sensing and Monitoring 399			
15.6	Limitations 400			
15.7	Conclusion 401			
	References 402			
16 Role of Carbon-Based Nanomaterials in CO ₂ Reduction and				
	Capture Reaction Process 411			
	Shyam Raj Yadav and Jai Prakash			
16.1	Introduction 411			
16.2	Parameters Affecting Electrocatalytic CO ₂ Reduction 412			
16.2.1	Onset Potential 412			
16.2.2	Overpotential (η) 414			
16.2.3				
	Current Density (j) 414			
16.2.4	Current Density (j) 414 Faradaic Efficiency (FE) 414			
16.2.4 16.2.5				
	Faradaic Efficiency (FE) 414			
16.2.5	Faradaic Efficiency (FE) 414 Tafel Analysis 414			
16.2.5 16.2.6	Faradaic Efficiency (FE) 414 Tafel Analysis 414 Turnover Frequency (TOF) and Turnover Number (TON) 415			
16.2.5 16.2.6 16.3	Faradaic Efficiency (FE) 414 Tafel Analysis 414 Turnover Frequency (TOF) and Turnover Number (TON) 415 CO_2 ECR-Derived Products 415			
16.2.5 16.2.6 16.3 16.4	Faradaic Efficiency (FE) 414 Tafel Analysis 414 Turnover Frequency (TOF) and Turnover Number (TON) 415 CO ₂ ECR-Derived Products 415 Plausible Mechanism for ECR of CO ₂ 417			
16.2.5 16.2.6 16.3 16.4 16.4.1	Faradaic Efficiency (FE) 414 Tafel Analysis 414 Turnover Frequency (TOF) and Turnover Number (TON) 415 CO_2 ECR-Derived Products 415 Plausible Mechanism for ECR of CO_2 417 Pathways for the Formation of C_1 Products 417			
16.2.5 16.2.6 16.3 16.4 16.4.1 16.4.1.1	Faradaic Efficiency (FE) 414 Tafel Analysis 414 Turnover Frequency (TOF) and Turnover Number (TON) 415 CO_2 ECR-Derived Products 415 Plausible Mechanism for ECR of CO_2 417 Pathways for the Formation of C_1 Products 417 Production of Formic Acid and Formate 417			
16.2.5 16.2.6 16.3 16.4 16.4.1 16.4.1.1	Faradaic Efficiency (FE) 414 Tafel Analysis 414 Turnover Frequency (TOF) and Turnover Number (TON) 415 CO ₂ ECR-Derived Products 415 Plausible Mechanism for ECR of CO ₂ 417 Pathways for the Formation of C ₁ Products 417 Production of Formic Acid and Formate 417 Formation of Carbon Monoxide (CO) 418			
16.2.5 16.2.6 16.3 16.4 16.4.1 16.4.1.1	Faradaic Efficiency (FE) 414 Tafel Analysis 414 Turnover Frequency (TOF) and Turnover Number (TON) 415 CO ₂ ECR-Derived Products 415 Plausible Mechanism for ECR of CO ₂ 417 Pathways for the Formation of C ₁ Products 417 Production of Formic Acid and Formate 417 Formation of Carbon Monoxide (CO) 418 Formation of Methane (CH ₄), Formaldehyde (HCHO), and			
16.2.5 16.2.6 16.3 16.4 16.4.1 16.4.1.1 16.4.1.2 16.4.1.3	Faradaic Efficiency (FE) 414 Tafel Analysis 414 Turnover Frequency (TOF) and Turnover Number (TON) 415 CO ₂ ECR-Derived Products 415 Plausible Mechanism for ECR of CO ₂ 417 Pathways for the Formation of C ₁ Products 417 Production of Formic Acid and Formate 417 Formation of Carbon Monoxide (CO) 418 Formation of Methane (CH ₄), Formaldehyde (HCHO), and Methanol (CH ₃ OH) 419			
16.2.5 16.2.6 16.3 16.4 16.4.1 16.4.1.1 16.4.1.2 16.4.1.3	Faradaic Efficiency (FE) 414 Tafel Analysis 414 Turnover Frequency (TOF) and Turnover Number (TON) 415 CO ₂ ECR-Derived Products 415 Plausible Mechanism for ECR of CO ₂ 417 Pathways for the Formation of C ₁ Products 417 Production of Formic Acid and Formate 417 Formation of Carbon Monoxide (CO) 418 Formation of Methane (CH ₄), Formaldehyde (HCHO), and Methanol (CH ₃ OH) 419 Pathways for the Production of C ₂₊ Products 420			

16.4.2.3	Formation of Acetone (CH ₃ COCH ₃) and <i>n</i> -propanol (CH ₃ CH ₂ CH ₂ OH) 421
16.5	Carbon-Based Nanomaterials in CO ₂ Reduction 422
16.5.1	Applications of Various Metal-Free Carbon-Based Nanomaterials
10.0.1	in CO ₂ Reduction 424
16.5.1.1	Carbon Nanofibers 424
16.5.1.2	Carbon Nanotubes 426
16.5.1.3	Nanoporous Carbon 429
16.5.1.4	Graphene 434
16.5.1.5	Nanodiamond 434
16.5.2	Applications of Various Metal-Carbon Composite Nanomaterials
	in CO ₂ Reduction 434
16.6	Imminent Challenges 436
16.7	Conclusion 438
	References 439
17	Application of Carbon Nanomaterials in CO ₂ Capture and Reduction 447
	R. Sanjeevi, J. Anuradh, and Sandeep Tripathi
17.1	Introduction 447
17.2	Different Types of Carbon Nanomaterials 448
17.2.1	Zero-Dimensional Carbon Nanomaterials 448
17.2.2	One-Dimensional Carbon Nanomaterials 448
17.2.3	Two-Dimensional Carbon Nanomaterials 449
17.2.4	Three-Dimensional Carbon Nanomaterials 449
17.2.5	Other Carbon Nanomaterials 449
17.2.5.1	Fullerenes: Spherical Marvels 449
17.2.5.2	Carbon Nanotubes (CNTs): Cylindrical Wonders 450
17.2.5.3	Graphene: The Thinnest Marvel 451
17.2.5.4	Nanodiamonds: The Small, Shining Gems 451
17.2.5.5	Carbon Nanohorns: Horn-Shaped Marvels 452
17.3	Applications in CO ₂ Management: Leveraging Unique Properties 452
17.4	CO ₂ Capture 453
17.4.1	The Imperative for CO ₂ Capture Technologies 453
17.4.2	Carbon Nanomaterials: Building Blocks for Capture 453
17.4.3	High Surface Area and Porosity: Key Features for CO ₂
	Adsorption 454
17.4.4	Nanoscale Efficiency: Enhanced CO ₂ Capture 454
17.4.5	Tailoring Surface Chemistry for Enhanced CO ₂ Adsorption 454
17.4.6	Dual Functionality 455
17.4.6.1	From Capture to Conversion 455
17.5	Catalytic Conversion of CO ₂ : Nanomaterials as Agents of Change 455

17.5.1	The Paradigm Shift: From Pollutant to Resource 456				
17.5.2	Carbon Nanomaterials as Catalysts: Unlocking Potential 456				
17.5.3	Electrochemical CO ₂ Reduction: Harnessing Electrical Energy 456				
17.5.4	Photocatalytic CO ₂ Reduction: Harvesting Solar Energy 457				
17.5.5	Metal Nanoparticles on Graphene: Catalysts for Sustainable CO ₂				
	Conversion 457				
17.5.5.1	Tunable Catalytic Activity 457				
17.5.5.2	Enhanced Electron Transfer 458				
17.5.5.3	Stability and Durability 458				
17.5.6	Selective CO ₂ Reduction: Tailoring Products for				
	Specific Applications 458				
17.5.6.1	Methane Production 458				
17.5.6.2	Ethylene Synthesis 458				
17.5.6.3	Carbon Monoxide Generation 459				
17.5.7	Challenges and Future Directions 459				
17.5.7.1	Catalyst Efficiency 459				
17.5.7.2	Reaction Selectivity 459				
17.5.7.3	Scalability and Practical Applications 459				
17.5.7.4	Environmental Impact 460				
17.5.7.5	Cross-Disciplinary Collaboration 460				
17.6	Challenges and Future Directions 460				
17.6.1	Scalability of Production Processes 460				
17.6.2	Long-Term Stability of Nanomaterials 461				
17.6.3	Economic Viability 461				
17.7	Future Directions 461				
17.7.1	Optimization of Synthesis and Engineering 461				
17.7.2	Exploration of Novel Catalytic Mechanisms 462				
17.7.3	Fundamental Interactions between Nanomaterials and CO ₂ 462				
17.7.4	Integration of Nanomaterials into Multi-Functional Systems 462				
17.7.5	Techno-Economic and Life Cycle Assessments 463				
17.7.6	Collaboration and Interdisciplinary Research 463				
17.8	Conclusion 463				
	References 464				
40					
18	Industrial Applications of Carbon Nanomaterials 469				
10.1	Y. Pathania, P. K. Ahluwalia, and Pooja Kapoor				
18.1	Introduction 469				
18.2	Different Forms of Carbon-Based Nanomaterials 471				
18.3	Applications of Carbon Nanomaterials 473				
18.3.1	Biomedical Industry 473				
18.3.1.1	Biosensors 473				

18.3.1.2	Drug Delivery 474
18.3.1.3	Biomedicine 475
18.3.1.4	Imaging 475
18.3.2	Energy Storage Industry 476
18.3.2.1	Batteries 476
18.3.2.2	Supercapacitors 477
18.3.2.3	Hydrogen Storage 477
18.3.3	Electronic Industry 478
18.3.3.1	Field-Effect Transistors and Digital Electronics 478
18.3.3.2	Wearable Electronics 479
18.3.3.3	Display Technology 479
18.3.4	Food Industry 480
18.3.4.1	Food Processing 480
18.3.4.2	Food Safety 481
18.3.4.3	Food Packaging 481
18.3.5	Aerospace Industry 481
18.3.5.1	Spacecraft and Satellite Applications 482
18.3.5.2	Commercial Aircraft Applications 482
18.3.5.3	Military Aircraft Applications 483
18.3.5.4	Rotorcraft Applications 483
18.3.5.5	Unmanned Aerial Vehicle (UAV) Applications 483
18.3.6	Environmental and Agricultural Sectors 484
18.3.6.1	Environmental Applications 484
18.3.6.2	Agricultural Applications 485
18.3.7	Automotive Industry 486
18.3.8	Green Energy Applications 486
18.4	Challenges 487
18.5	Conclusions and Future Scope 488
	Acknowledgment 489
	Declarations 489
	Funding 489
	References 489
19	Carbon-Based Nanomaterials and Their Green Energy Applications:
	Carbon Nanotubes 505
	Smita Singh, Varsha Singh, Vikram Rathour, and Vellaichamy Ganesan
19.1	Introduction 505
19.1.1	Carbon Nanomaterials 506
19.1.2	Fullerenes (C ₆₀) 506
19.1.3	Carbon Nanotubes 507
19.1.4	Graphene 508

19.2	Synthesis of CNTs 509			
19.2.1	Plasma-Based Synthesis 509			
19.2.2	Thermal-Based Synthesis 510			
19.3	Properties of Carbon Nanotubes 511			
19.3.1	Mechanical Properties of CNTs 511			
19.3.2	Electrical Properties of CNTs 511			
19.3.3	Thermal Properties of CNTs 512			
19.3.4	Optical Properties of CNTs 513			
19.3.5	Chemical Properties of CNTs 513			
19.4	Green Energy Applications of CNTs 514			
19.4.1	Supercapacitors 514			
19.4.2	HER 515			
19.4.3	OER 518			
19.4.4	ORR 521			
19.4.5	Electrochemical Sensors 523			
19.5	Challenges Associated with CNTs 523			
19.5.1	Synthesis and Purity 524			
19.5.2	Scaling Up Production 524			
19.5.3	Functionalization and Dispersion 524			
19.5.4	Electrode Fabrication 524			
19.5.5	Chemical and Environmental Stability 524			
19.6	Conclusion 524			
	Acknowledgments 525			
	References 525			
20	Carbon-Based Nanoparticles as Visible-Light Photocatalysts 533			
	Sonam Soni			
20.1	Introduction 533			
20.1.1	Application of Green Energy 534			
20.1.2	Importance of Photocatalytic Technique 534			
20.1.3	Importance of Nanotechnology in Visible Light Photocatalysis 535			
20.2	Mechanism of Photocatalysis 536			
20.2.1	Oxidation Mechanism 536			
20.2.2	Reductive Mechanism 537			
20.3	Classification of Nanomaterials 537			
20.4	Types of Carbon-Based Nanoparticles 538			
20.5	Application of CNPs as Photocatalysts 538			
20.5.1	Photocatalytic Splitting of Water for Hydrogen Production 539			
20.5.1.1	Factors Affecting Photocatalytic Splitting of Water 541			
20.5.2	Photodegradation of Organic Pollutants 542			
20 5 2 1	Mechanism of Photocatalytic Degradation 544			

20.5.2.2	Factors Influencing Degradation of Organic Pollutants by $g-C_3N_4/CQDs$ 545
20.6	Conclusions 548
20.7	Future Scope 548
	References 549
21	Cauban Based Namematavials in Day to Day Human Life 552
21	Carbon-Based Nanomaterials in Day-to-Day Human Life 553 Manju Choudhary, Pooja Nain, Shivanshu Garg, and Himanshu Punetha
21.1	Introduction 553
21.2	Utilization of CNPs in Medical Services 555
21.2.1	Pathological Condition Detections 555
21.2.1.1	Detection Relying on Adsorption of Metabolites 558
21.2.1.2	Bioimaging by Photoacoustics 559
21.2.1.2	Protection from Penetration Power of X-Rays 559
21.2.1.4	Changing Dynamic State by Photodynamic Therapy 559
21.2.1.5	Temperature-Induced Transformations Through
	Photothermal Treatment 560
21.2.1.6	Raising Immune Responses by Vaccination 561
21.2.1.7	Generation of Artificial Tissue Implants 561
21.2.1.8	Engineering Tissues and Tissue Metabolites 562
21.2.1.9	Drug Targeting and Drug Delivery Approaches 563
21.3	Applications Pertaining to Electrical and Electronics Sectors 563
21.3.1	Radar Waves Absorption by CNPs 563
21.3.2	Nanoparticles Implanted on Chip 564
21.3.3	Developing Nanosensors 564
21.3.3.1	Gas Phase Nanosensors 565
21.3.3.2	Optical Detection Nanosensors 565
21.3.4	Light-Emitting Diode Screens Implanted With Nanomaterials 565
21.3.5	Conserving Charge via Nanobatteries 565
21.4	Applications Pertaining to Wind and Solar Energies 566
21.4.1	The Charge Held by Nanomaterials as Supercapacitors 566
21.4.2	Energy Conservation by Fuel Cells 567
21.4.3	Lithium-Ion Batteries: A Run for Electric Vehicles 569
21.5	Application Pertaining to Food Industry Sector 571
21.5.1	Nanoencapsulation: An Approach to Increasing Shelf-Life 571
21.5.2	Nanoemulsification: An Aid to Food Digestion 571
21.5.3	Nanomaterial Levels in Food Packaging 571
21.5.3.1	Type 1: Active Packaging 572
21.5.3.2	Type 2: Intelligent and Responsive Packaging 572
21.5.3.3	Type 3: Smart Packaging 572
21.6	Nanoparticles Operating Within Soil 573

21.6.1	Clay Particles 573			
21.6.2	Humic Substances: Humidifying Agents in Soil 573			
21.6.3	Fulvic Acids: A Response Toward Soil Salinity 574			
21.7	Agricultural Aspects of Nanomaterials 574			
21.8	Nanomaterials Bringing Out Latest Revolutions 575			
21.8.1	Fuel of Nucleotide Triphosphates (NTPs) 575			
21.8.2	Hybridization of Nanomaterials to Achieve Sustainability 575			
21.8.3	Membranous Carbon Nanotubes Role in Removing			
	the Micro-Pollutants 575			
21.8.4	Drug Delivery Targeting to Malignant Neurons 576			
21.8.5	DNA Origami Nanoturbine and Nanomotor Revolutions 576			
21.8.5.1	Nanoturbines and Generation of Mini-Multi-Powers 576			
21.8.5.2	Induction of Power Performance of Potassium-Ion Batteries 577			
21.9	Conclusion and Future Scope 577			
	References 578			

Index 587

About the Editors

Dr. Upendra Kumar

Dr. Upendra Kumar is an assistant professor at the Department of Applied Sciences, Indian Institute of Information Technology Allahabad, Prayagraj. He received his bachelor and masters degrees in physics from Banaras Hindu University, Varanasi, and his PhD from IIT (BHU), Varanasi. Before joining IIIT Allahabad, he also worked as an assistant professor in Banasthali Vidtapith, Rajasthan, and gained teaching, research, and administrative experiences. He has two major research projects from the SERB, Govt. of India, and IIIT Allahabad. He has successfully supervised two PhD students, and four are still working in his mentorship. He has also supervised several MSc and MTech projects. He has published over 100+ research articles, including highly reputed international and national journals, conference proceedings, books, book chapters, and the ICDD database. He has also received a prestigious membership in the National Academy of Sciences India (NASI) and is a senior-grade member of IEEE Professional. Currently, he is also working as a secretary for the IEEE Photonics Society UP chapter. He is an academic editor for the journal Advances in Condensed Matter Physics (Wiley) and a member of many scientific societies such as IAPT, IPA, IEEE Young Professional, etc. He also served as the referee for international journals of Elsevier, Springer, Wiley, Taylor & Francis, and ACS, and a topical advisory panel member of many MDPI journals. His extensive research areas are electroceramics, solid oxide fuel cells, piezoelectric ceramics, microwave dielectric, machine learning, computational materials science, energy generation, and storage materials.

Personal Homepage: https://sites.google.com/view/drupendrakumar/home Researchgate: https://www.researchgate.net/profile/Upendra-Kumar-7 Google Scholar: https://scholar.google.com/citations?user=rOYIerMAAAAJ&hl=en

Dr. Piyush Kumar Sonkar

Dr. Piyush Kumar Sonkar has received his BSc (Chemistry), MSc (Chemistry), and PhD (Chemistry) degrees from Banaras Hindu University, India. He is an assistant professor in the Department of Chemistry, MMV, Banaras Hindu University, Varanasi, India. He has teaching and research experience of 11 and 6 years, respectively. His research interests include nanomaterials, nanocomposites, metal complexes, fuel cells, electrochemical devices, supercapacitors, biosensors, chemical sensors, and new materials. He has published 47 international and national research papers in various reputed peer-reviewed journals. He has published six book chapters. He is the editor of two international books on nanomaterials. He has completed two research projects at UGC, New Delhi, and IoE BHU. Currently, one research project is under his supervision based on tribal medicines. He has presented his research work in various international/national seminars/ workshops and conferences. Currently, two PhD students are working under his supervision.

Google Scholar Link:

https://scholar.google.co.in/citations?user=7WQwcscAAAAJ&hl=en Research Gate Link: https://www.researchgate.net/profile/Piyush_Sonkar Institute Profile Link: https://bhu.ac.in/Site/FacultyProfile/1_225?FA000575

Dr. Suman Lata Tripathi

Dr Suman Lata Tripathi is working as a professor at Lovely Professional University and has more than 22 years of experience in academics and research. She has completed her PhD in microelectronics and VLSI Design from MNNIT, Allahabad. She did her MTech in electronics engineering from UP Technical University, Lucknow, and her BTech in electrical engineering from Purvanchal University, Jaunpur. She completed her remote post-doc from Nottingham Trent University, London, UK, in 2022-2023. She has published more than 152 research papers in refereed Springer, Elsevier, IEEE, Wiley, and IOP science journals, conference proceedings, and e-books. She has also published 20 Indian patents and 4 copyrights. She has guided six PhD scholars, and three are in the submission stage. She has been listed in the world's top 2% of scientists published by Stanford University for 2024. She has organized workshops, summer internships, and expert lectures for students. She has worked as a session chair, conference steering committee member, editorial board member, and peer reviewer in international/national IEEE, Springer, Wiley, etc. journals and conferences. She is a visiting professor at Telkom University, Indonesia. She received the "Research Excellence Award" in 2019 and the "Research Appreciation Award" in 2020, 2021, and 2023 at Lovely Professional University, India. She received the IGEN Women's for Green Technology

"Women's Achievers Award" on International Women's Day, 8 March 2023. She received the best paper at IEEE ICICS-2018. She has also received a funded project from SERB DST under the TARE scheme in microelectronics devices. She has edited and authored more than 30 books in different areas of electronics and electrical engineering. She is associated with editing work with top publishers like Elsevier, CRC Taylor & Francis, Wiley-IEEE, SP Wiley, Nova Science, and Apple academic press. She is also working as a book series editor for the title "Smart Engineering Systems" CRC Press; "Engineering System Design for Sustainable Developments," "Decentralized Systems," and "Next Generation Internet" Wiley-Scrivener; and conference series editor for "Conference Proceedings Series on Intelligent Systems for Engineering designs" CRC Press Taylor & Francis. She is serving as academic editor of "Journal of Electrical and Computer Engineering" (Scopus/WoS, Q2), "International Journal of Reconfigurable Computing" (Scopus, Q3), "Active and Passive Electronic Component" (Scopus, Q4) Hindawi-Wiley and special issue guest editor for "Advances in Nanomaterials and Nanoscale Semiconductor Applications" Material, MDPI Journal (SCI IF=3.74, Q2). She is associated as a senior member of IEEE, a Fellow IETE, and a Life member of ISC, and she is continuously involved in different professional activities and academic works. Her area of expertise includes microelectronics device modeling and characterization, low-power VLSI circuit design, VLSI design of testing, advanced FET design for IoT, embedded system design, reconfigurable architecture with FPGAs and biomedical applications, etc.

Google Scholar profile link:

https://scholar.google.com/citations?hl=en&user=SdbROCAAAAAJ&view_ op=list_works

Research gate profile link: https://www.researchgate.net/profile/Suman-Tripathi

Scopus profile link:

https://www.scopus.com/authid/detail.uri?authorId=57564799800 Institute Profile: https://vidwan.inflibnet.ac.in//profile/282457/