

POLYMER CIRCULARITY IN SUSTAINABLE ENERGY

EDITED BY
SABU THOMAS
BRUNO AMEDURI
JINCE THOMAS
MARTIN GEORGE THOMAS



Polymer Circularity in Sustainable Energy

This page intentionally left blank

Polymer Circularity in Sustainable Energy

Edited by

Sabu Thomas

Mahatma Gandhi University, Kottayam, Kerala, India
Department of Physics and Electronics, Christ University, Bangalore,
Karnataka, India
Center of Excellence in Polymeric Materials for Medical Practice Devices,
Department of Chemical Engineering, Faculty of Engineering,
Chulalongkorn University, Bangkok, Thailand
Polymer and Process Engineering, IIT Roorkee, Uttarakhand, India

Bruno Ameduri

Institute Charles Gerhardt, University Montpellier, CNRS,
ENSCM, Montpellier, France

Jince Thomas

Department of Mechanical and Industrial Engineering,
University of Toronto, ON, Canada

Martin George Thomas

Department of Physics and Electronics, Christ (Deemed to be University),
Bengaluru, Karnataka, India



Elsevier

Radarweg 29, PO Box 211, 1000 AE Amsterdam, Netherlands
125 London Wall, London EC2Y 5AS, United Kingdom
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States

Copyright © 2027 Elsevier Inc. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

For accessibility purposes, images in electronic versions of this book are accompanied by alt text descriptions independently provided by Elsevier, generated with the aid of AI. For more information, see <https://www.elsevier.com/about/accessibility> or Radarweg 29, 1043 NX Amsterdam, Netherlands.

Books and Journals published by Elsevier comply with applicable product safety requirements. For any product safety concerns or queries, please contact our authorised representative, Elsevier B.V., at productsafety@elsevier.com.

Publisher's note: Elsevier takes a neutral position with respect to territorial disputes or jurisdictional claims in its published content, including in maps and institutional affiliations.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: www.elsevier.com/permissions.

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

ISBN: 978-0-443-27739-9

For information on all Elsevier publications visit our website at
<https://www.elsevier.com/books-and-journals>

Publisher: Matthew Deans

Acquisitions Editor: Jinia Dasgupta

Editorial Project Manager: Debarati Roy

Production Project Manager: Maria Shalini

Cover Designer: Bakyalakshmi S.

Typeset by TNQ Tech



Contents

Contributors	xxi
About the editors	xxvii
Preface	xxix

SECTION I Polymer circularity: Fundamentals, regulations, and recycling

CHAPTER 1 Fundamentals of polymer chemistry	3
<i>Emma Franco-Mateos, Cecilia Chaine and María Blecua</i>	
1 Introduction	3
2 Basic concepts	4
2.1 Average molecular weight and polydispersity index.....	5
2.2 Configurations and conformations	5
2.3 Types of polymerizations	7
3 Properties	9
3.1 Dissolution of polymers: solubility.....	9
3.2 Solid state: Viscoelasticity behavior	9
3.2 Thermal transitions and properties.....	12
3.3 Degradation and stability	15
4 Classification of polymers.....	16
4.1 Composition and structure	18
4.2 Polymeric binary or multi-systems: polymeric blends and composite polymeric materials	21
4.3 Types of polymers and classification by properties.....	25
5 Key concepts overview	27
References.....	27
CHAPTER 2 Regulatory frameworks and policies for polymer recycling.....	29
<i>Elíana Díaz-Cruces and Camilo Zamora-Ledezma</i>	
1 Introduction	29
2 Origins and evolution of the regulatory framework in polymer recycling.....	31
2.1 From waste management to recycling	31
2.2 Toward a circular economy: principles and normative frameworks.....	32
2.3 Key global policy instruments	33
2.4 International perspectives and global cooperation	35
3 Multi-level regulatory frameworks: European union, Spain, and the community of madrid.....	38
3.1 European union regulatory framework	38
3.2 National developments in Spain	39

3.3 Regional regulation: law January 2024 on circular economy of community of madrid.....	42
4 Technological innovation and digitalization as regulatory enablers.....	45
5 Best practices and lessons learned.....	46
6 Conclusions and recommendations.....	48
AI disclosure.....	49
References.....	49
CHAPTER 3 Advancing polymer reuse: Mechanical and chemical recycling methods.....	55
<i>Ricardo Abejón</i>	
1 Introduction.....	55
2 Mechanical recycling.....	58
2.1 Processing technologies in mechanical recycling.....	59
2.2 Mechanical recycling of polyolefins.....	63
2.3 Mechanical recycling of polyvinyl chloride (PVC).....	65
2.4 Mechanical recycling of polystyrene (PS).....	68
3 Chemical recycling.....	69
3.1 Pyrolysis.....	69
3.2 Liquefaction.....	70
3.3 Gasification.....	75
3.4 Solvolysis.....	78
3.5 Other catalytic approaches for chemical recycling of polymers.....	85
4 Conclusions.....	89
AI disclosure.....	90
References.....	90
CHAPTER 4 Controlling halogens in the plastic resource circulation.....	107
<i>Haru Ishikawa, Yuko Saito, Toru Nishiyama, Shogo Kumagai and Toshiaki Yoshioka</i>	
1 Introduction.....	107
2 Wet dechlorination process and chlorine circulation for PVC and mixed plastics.....	107
3 Functionalization of PVC by nucleophilic substitution reactions.....	112
4 Metal recovery through pyrolysis of PVC and mixed plastics.....	114
5 Defluorination and recovery of fluorine (fluorine circulation) from fluoropolymers.....	117
6 Debromination from plastics containing brominated flame retardants.....	121
7 Conclusion.....	124
References.....	125

SECTION II Polymer degradation: Deterioration characteristics and dynamics

CHAPTER 5 Surface chemistry of polymer degradation	131
<i>Yingjun An, Adchara Padermshoke, Tomoko Kajiwara and Atsushi Takahara</i>	
List of symbols and abbreviations	131
1 Introduction	132
2 Chemical degradation of polymeric solids	136
2.1 Thermal decomposition	136
2.2 Oxidative decomposition	137
2.3 Photodegradation	138
3 Biodegradation	141
4 Physical degradation	145
4.1 Tensile strength of polymeric solids	146
4.2 Scratch resistance	146
4.3 Environmental stress cracking	149
5 Conclusion	150
Acknowledgements	151
References	151
CHAPTER 6 “Light activation for polymer circularity”—Chapter in “polymer circularity in sustainable energy”	157
<i>Kaidan Yang and Jacques Lalevée</i>	
1 Introduction	157
2 Mechanistic foundations of light-responsive materials	158
2.1 Photothermal conversion	158
2.2 Dynamic chemical bonds	164
2.3 Photocatalytic and photochemical mechanisms	168
3 Light-driven material design	175
3.1 Programmable polymer networks	175
3.2 Composite system design	179
3.3 Advanced manufacturing technologies	182
4 Applications for sustainable materials	183
4.1 Light-triggered self-healing materials	183
4.2 Circular economy and sustainability	187
5 Outlook	195
References	196

CHAPTER 7 Technological advances in polymer sorting and separation 209*Muhammad Naseem Akhtar and Norah Al Fayeze*

1	Introduction	209
2	Manual separation	210
3	Density-based separation	210
3.1	Sink-float	211
3.2	Hydrocyclones	213
3.3	Air classifiers	215
3.4	Magnetic Density Separation (MDS)	216
3.5	Supercritical CO ₂	217
4	Froth flotation	218
5	Optical-based separation	220
5.1	Color-based separation	220
5.2	Mid-infrared (MIR) spectroscopy	221
5.3	Near-infra-red (NIR) spectroscopy	223
5.4	Raman spectroscopy	225
5.5	Laser-induced breakdown spectroscopy (LIBS)	226
5.6	X-ray fluorescence (XRF) spectroscopy	226
6	Triboelectric separation	228
7	Thermal-based plastic separation using melting point differences	231
8	Solubility-based plastic separation	232
9	Hybrid systems	233
9.1	Triboelectric and air classification	234
9.2	Density separation and NIR spectroscopy	234
9.3	Magnetic Density Separation (MDS) and optical sorting	234
9.4	Cryogenic and electrostatic separation	234
9.5	Solubility and spectroscopic sorting	234
10	Latest advanced techniques	234
10.1	AI & robotics for smart sorting of plastic waste	235
10.2	Fluorescent markers for plastic identification and sorting	237
10.3	Hyperspectral imaging (UV-Vis-NIR)	239
11	Conclusion	240
	References	240

CHAPTER 8 Degradation, recycling, and post treatment of perfluorosulfonic acid membranes for fuel cells 245*Pranav Omanakuttan, Martin George Thomas, Bruno M. Ameduri and Sabu Thomas*

1	Introduction	245
2	Structure and properties of PFSA membranes	248
2.1	Chemical composition and architecture	248

2.2	Physical and electrochemical properties	250
2.3	Membrane—electrode assembly (MEA) integration	252
3	Degradation mechanisms of PFSA membranes	252
3.1	Chemical degradation	252
3.2	Mechanical degradation	254
3.3	Thermal and hydrolytic degradation	254
3.4	Diagnostic methods for membrane health	255
4	End-of-life management of PFSA membranes	257
4.1	Current disposal practices	257
4.2	Recycling techniques	258
4.3	Environmental and regulatory considerations	260
5	Circular strategies for PFSA membranes	261
5.1	Recovery and regeneration	261
5.2	Design-for-recycling principles	262
5.3	Integration into the circular economy	263
5.4	Carbon footprint and life cycle analysis (LCA)	265
6	Handling after degradation and recycling	265
6.1	Safe storage and transport	265
6.2	Quality assessment and reuse criteria	266
6.3	Disposal of irrecoverable material	267
7	Global perspectives and policy linkages	269
7.1	Sustainability in fuel cell materials	269
7.2	International regulations and standards	270
7.3	Industry initiatives and case studies	271
8	Current status and future outlook	272
9	Conclusions	274
	References	275

SECTION III Primary polymers in a circular economy

CHAPTER 9	Circular management of single-use polyolefins via hydrocracking over zeolite-based catalysts	289
	<i>Muhammad Usman Azam, Muhammad Umer, Inês Graça and Waheed Afzal</i>	
1	Introduction	289
2	Catalytic hydrocracking of plastics	291
3	Effect of physicochemical properties of zeolites	293
3.1	Role of acidity and acidic strength of zeolite	294
3.2	Influence of the pore structure in zeolite catalyst design	299
4	Optimizing hydrocracking of plastic: investigating the influence of reaction conditions	309

4.1 Effect of reaction temperature	309
4.2 Effect of reaction time	311
4.3 Effect of hydrogen pressure	312
4.4 Effect of polymer type	313
5 Conclusion	314
References	315
 CHAPTER 10 Chemical recycling of poly(siloxane)s: Is depolymerization to cyclic monomers the only way?	319
<i>Daniel Portinha, Etienne Fleury and Serena Kocyan</i>	
1 Context and generalities	319
2 Recycling silicones toward monomers	322
3 Toward functional oligomers	324
4 Toward the recycling of silicone materials via dynamic covalent chemistry	331
4.1 Vitrimer silicone elastomers with associative functions	332
4.2 Vitrimer silicone elastomers	334
5 Conclusion	339
AI disclosure	340
References	340
 CHAPTER 11 Recycled polyurethanes: Applications in renewable energy technologies	343
<i>Karmuhil Mathimozhiyazh Vetriselvan, Sathyaprakash Sreenivasan, Ashwanth Pari, Rohitha Devaraj, Sekaran Ganesan and Ramani Kandasamy</i>	
1 Introduction	343
2 Polyurethane chemistry and lifecycle	344
2.1 Structure and properties of polyurethanes	344
2.2 Types of polyurethanes	345
2.3 Flexible polyurethane foams	345
2.4 Thermoplastic polyurethanes	345
2.5 Polyurethane ionomers	346
2.6 Common uses and end-of-life challenges	346
3 Recycling techniques for polyurethanes	347
3.1 Mechanical recycling	347
3.2 Regrinding	347
3.3 Rebonding	348
3.4 Adhesive pressing	348
3.5 Compression molding	349
3.6 Chemical recycling	349
3.7 Glycolysis	350

3.8 Alcoholysis	351
3.9 Fractionation	351
3.10 Hydroglycolysis	351
3.11 Aminolysis	351
3.12 Feedstock recycling	352
3.13 Gasification	352
3.14 Hydrogenation	352
3.15 Energy recovery	353
3.16 Municipal waste combustion	353
3.17 Fluidized bed combustion	353
3.18 Two stage incineration	354
3.19 Rotary kiln combustion	354
3.20 Thermal degradation	354
3.21 Biodegradation of polyurethane	354
3.22 Recycled PU in renewable energy systems	355
3.23 PU foams in wind turbine blades and components	355
3.24 PU elastomers in hydropower and marine applications	356
3.25 PU applications in energy storage systems (batteries, supercapacitors)	356
3.26 PU application in triboelectric nanogenerator	356
4 Environmental and economic assessment	356
4.1 Market size	360
4.2 Economic assessment	360
4.3 Life cycle assessment	360
4.4 Challenges and future prospects	361
5 Conclusion	361
Acknowledgment	362
References	362
Further readings	367

CHAPTER 12 Poly(vinylidene fluoride) in piezo and triboelectric technologies: From principles and processing to recycling and reuse strategies

C.M. Costa, R. Brito-Pereira, P. Costa and S. Lanceros-Méndez

1 Introduction to poly(vinylidene fluoride)	369
2 Principles of piezoelectric and triboelectric technologies	372
2.1 Fundamentals of piezoelectricity	372
2.2 Fundamentals of triboelectricity	374
2.3 Manufacturing of piezo- and triboelectric devices	375
3 Recycling and reuse strategies for polyvinylidene fluoride waste	377
3.1 Recycling and reuse of polyvinylidene fluoride	377
3.2 Environmental impact and life-cycle assessment	379

4 Reuse of recycled PVDF in piezoelectric and triboelectric technologies	380
5 Challenges and future outlook	381
Acknowledgments	382
References	382

SECTION IV Circular polymer strategies for energy systems

CHAPTER 13 Recycling and reuse of polymers in photovoltaic technologies 389

Upakar Patel and Pralay Maiti

1 Introduction	389
2 Types and roles of polymers in photovoltaics	393
2.1 Encapsulants	394
2.2 Backsheet materials	394
3 Challenges in recycling polymers from PVs	396
4 Recycling methods	399
4.1 Mechanical recycling	399
4.2 Chemical recycling	399
4.3 Thermal recycling	400
4.4 Module disassembly approaches	402
5 Reuse possibilities and second-life applications	403
5.1 Reuse of polymer films	403
5.2 Upcycling approaches	403
5.3 Circular economy frameworks for PV polymers	404
5.4 Direct reuse of modules or components	405
5.5 Repurposing waste polymers in other industries	405
5.6 Innovative upcycling approaches	406
6 Innovations and research in polymer reuse	406
7 Innovative approaches and future perspectives	408
8 Policy and regulations	408
9 Need for standardization	409
10 Vision for a circular economy in photovoltaics	409
11 Conclusions	410
Acknowledgment	411
References	411

CHAPTER 14 Recycling and reuse of polymers in fuel cells 415

Bholanath Ghanti and Susanta Banerjee

1 Introduction	415
2 Fuel cells (FCs)	416
2.1 Brief history	417
2.2 Types or classifications	418

3	Recycling and reuse of polymer in PEMFCs	425
4	Recycling and reuse of polymer in CEMFCs	426
4.1	Presentation, characteristics, and other features of CEMFCs	426
4.2	Recycling and reuse of CEMs	428
5	Recycling and reuse of polymers in AEMFCs	435
5.1	Presentation, characteristics, and other features of AEMFCs	435
5.2	Recycling and reuse of AEMs	435
6	Conclusion	437
	Authors' contribution	438
	Acknowledgments	438
	Declaration of conflicts of interest	438
	References	438
	Further reading	446
CHAPTER 15	Recycling of polymers in space energy systems	447
	<i>Mohammad Harun-Ur-Rashid, Abu Bin Imran and</i>	
	<i>Md. Abu Bin Hasan Susan</i>	
1	Introduction	447
2	Polymers in space energy systems	448
2.1	Types of polymers used in space technologies	448
2.2	Roles of polymers in space energy generation and storage	450
2.3	Degradation mechanisms of polymers in space environments	450
3	Challenges of recycling polymers in space	451
3.1	Physical and chemical limitations in microgravity	452
3.2	Resource and energy constraints	453
3.3	Material contamination and purity issues	453
3.4	Reliability and durability of recycled polymers	454
4	Recycling technologies for polymers in space	454
4.1	Mechanical recycling approaches	454
4.2	Chemical recycling approaches	455
4.3	Biological recycling methods	456
4.4	ISRU strategies	456
5	Emerging innovations in space polymer recycling	457
5.1	Additive manufacturing and recycling integration	457
5.2	Smart recycling systems with AI and robotics	458
5.3	Self-healing polymers and future recycling prospects	458
5.4	Hybrid recycling technologies: combining mechanical, chemical, and biological routes	459
6	Comparative analysis of recycling strategies	459
6.1	Efficiency comparison of mechanical, chemical, and biological recycling	459
6.2	Environmental impact assessment of various methods	461
6.3	Energy consumption and material recovery rates	462

7	Case studies and real-world applications	463
7.1	Sabatier recycling system of NASA	464
7.2	Closed-loop material recycling projects of the European Space Agency.....	464
7.3	Private sector innovations: SpaceX, Blue Origin, and beyond	465
8	Future prospects and recommendations.....	465
8.1	Designing polymers for enhanced recyclability	465
8.2	Integration of recycling with space habitat construction	466
8.3	Policy and international collaboration for space sustainability.....	466
9	Conclusion	467
	Conflict of interest statement	468
	References.....	468

CHAPTER 16 Sustainable soft bioelectronic sensors: From biopolymers and eutectic solvents to eutectogels..... 475

Pablo A. Mercadal and Agustín González

1	Introduction	475
2	DES: Fundamentals and green aspects.....	476
2.1	Thermodynamics of DES.....	476
2.2	Type of DES	478
2.3	Synthesis and physicochemical properties of DES relevant to wearable biosensors for biomedical applications.....	479
3	Biopolymers for soft bioelectronic sensors	483
3.1	Gelatin	483
3.2	Alginate	485
3.3	Cellulose	485
3.4	Poly(vinyl alcohol).....	486
4	Bio-based eutectogels: Processing biopolymers with DES and recent advances in wearable bioelectronic sensors	486
4.1	Synthesis of eutectogels	486
4.2	Types of eutectogels	488
4.3	Properties of eutectogels	488
4.4	Recent advances in wearable bioelectronic sensors	491
5	Conclusion, challenges and perspectives.....	493
	AI disclosure.....	493
	References.....	493

CHAPTER 17 Polymer binders in battery electrodes: Sustainable recovery and recycling strategies 503

Sanna Gull, Masimukku Srinivaas and Guy Olivier Ngongang Ndjawa

1	Introduction	503
2	Binders in batteries	504
2.1	Functions of binders in battery electrodes.....	506

3	Water-based and bio-based binders	509
3.1	Carboxymethyl cellulose (CMC)	509
3.2	Styrene butadiene rubber (SBR)	509
3.3	Polyacrylic acid (PAA).....	510
3.4	Emerging and bio-based/sustainable binders.....	511
4	Multifunctional binders for next-generation battery chemistries.....	511
5	Recovery methods	512
6	Cost and scalability of binder recovery techniques.....	515
7	Future outlook	516
7.1	Recyclable binder design	516
7.2	Binder-free alternatives	517
8	Conclusion.....	517
	References.....	518

CHAPTER 18 Valorization of lignocellulosic biomass into fermentable sugars for production of biofuels..... 523

*Ronald Marquez, Roberto J. Aguado, Quim Tarres, Hasan Jameel
and Marc Delgado-Aguilar*

	List of abbreviations	523
1	Introduction	524
2	Composition and characteristics of lignocellulosic feedstocks.....	525
2.1	Cellulose-hemicellulose interfacial assembly	529
2.2	Lignin-carbohydrate complexes (LCCs).....	530
2.3	Common lignocellulosic feedstocks for biofuel production	530
2.4	Factors influencing conversion.....	533
3	Pretreatment of lignocellulosic biomass.....	534
3.1	Mechanical refining and thermomechanical pretreatment (low to zero chemicals).....	535
3.2	Energy considerations in mechanical pretreatment	540
3.3	Combined thermomechanical-chemical pretreatment	541
4	Enzymatic engineering for lignocellulose deconstruction and modification to fermentable sugars	542
4.1	Mechanism of enzymatic action and factors affecting efficiency.....	544
4.2	Enzyme-substrate interactions and catalysis.....	548
4.3	Non-productive enzyme adsorption onto lignin	550
4.4	Kinetic modeling of lignocellulose enzymatic hydrolysis	551
5	Fermentation of hydrolyzates to biofuels and biochemicals.....	552
5.1	Advanced microbial cell factories for valorization of hydrolyzates.....	553
5.2	Kinetic modeling of microbe-mediated fermentation	554
5.3	Machine learning for predictive modeling in biomass valorization.....	557
6	Conclusions and future perspective	558
	References.....	559

SECTION V Plastic waste transformation for a circular economy

CHAPTER 19 Upcycling of polymer waste into high value energy products 571

Betül Aksoy, Yasemin Ozlman and Melih Soner Celiktaş

1	Introduction	571
2	Polymer waste structure	573
2.1	Categorization of polymers based on type of polymerization	573
2.2	Structural analysis	574
2.3	Elemental analysis	574
2.4	Thermal analysis	575
2.5	Additives	576
2.6	Management of polymer wastes	576
3	Conventional methods and existing solutions for waste polymer management	577
3.1	Disposal	577
3.2	Incineration	578
3.3	Mechanical recycling	578
4	Process frameworks of upcycling methods	579
4.1	Biological methods	579
4.2	Chemical methods	580
4.3	Thermal methods	581
4.4	Electrochemical and photochemical methods	582
4.5	Cutting-edge methods	583
5	Utilization of upcycled polymer waste for energy products	585
5.1	Carbon materials	585
5.2	Fuels	586
5.3	Electrical energy storage	587
5.4	Solar steam generator	587
6	Barriers to effective upcycling	587
6.1	Technical barriers	587
6.2	Economic barriers	588
6.3	Systemic barriers	588
7	Opportunities and emerging pathways for polymer waste upcycling	588
8	Conclusion	589
	Funding	589
	Contributions	590
	References	590

CHAPTER 20 Strategies for upcycling perfluoroalkyl substances and aromatic plastic waste into high performance materials 605

Gustavo Muñoz, Maxim Solovyev and Dennis W. Smith, Jr.

1	Introduction	605
2	Sustainable polymers	606

3	Current techniques for managing and disposing of PFAS	608
3.1	Thermal degradation/incineration	608
3.2	Electrochemical oxidation	609
3.3	Plasma	609
3.4	Supercritical water oxidation	609
3.5	Sonolysis	609
4	Interfacial polymerization of hexafluoroacetone	610
4.1	Polymerization of oxygen-containing aromatic monomers with hexafluoroacetone	610
4.2	Polymerization of nonactivated aromatic monomers with hexafluoroacetone	612
4.3	Application of 6F polymers in fuel cells	615
5	Upcycling of polymers via fluoroalkylation using derivatives of perfluorinated carboxylic acids	615
5.1	Fluoroalkylation of aromatic polymers by using perfluoroalkanoyl peroxides	616
5.2	Fluoroalkylation of aromatic polymers by using fluorinated anhydrides	617
5.3	Fluoroalkylation of aromatic compounds by hypervalent iodine (III) reagents (HIRs)	617
6	Upcycling of olefins derived from perfluorinated carboxylic acids	619
7	Summary	623
	References	623

CHAPTER 21 Feedstock recycling of waste plastics through pyrolysis technologies 629

*Kazuki Fujiwara, Shogo Kumagai, Toru Nishiyama, Yuko Saito
and Toshiaki Yoshioka*

1	Introduction	629
2	Pyrolysis	630
3	Catalytic pyrolysis for liquefaction	633
4	Catalytic pyrolysis for gasification	647
5	Conclusion	658
	Acknowledgment	659
	References	659

CHAPTER 22 Recycling fuel cell components: Strategies for a circular hydrogen economy 663

*Eirini Zagoraiou, Anastasia-Maria Moschovi, Ekaterini Polyzou and
Iakovos Yakoumis*

	List of abbreviations	663
1	Introduction	664

2	Overview of PEMFC technology and key components	665
2.1	Critical components of PEMFCs	666
2.2	Lifespan and degradation mechanisms	668
3	Recycling strategies in PEMFCs	670
3.1	Stack disassembly.....	671
3.2	MEA delamination	672
3.3	Electrocatalysts recycling.....	673
3.4	Polymer materials recycling.....	678
3.5	Functional components recycling	682
3.6	MONOLITHOS' recycling process	686
4	Design for recycling and circularity	690
4.1	Eco-design principles in fuel cell manufacturing.....	692
4.2	Modular fuel cell architecture.....	693
4.3	Sustainable materials substitution	694
5	Industrial case studies and best practices	696
5.1	Automotive sector	696
5.2	Stationary and portable fuel cells	699
6	Technological and economic challenges of PEMFCs recycling.....	700
6.1	Materials complexity and components integration.....	701
6.2	Degradation effects on recyclability	702
6.3	Economic viability of recycling operations.....	703
6.4	Strategic opportunities and end-of-life management strategies for overcoming recycling barriers.....	704
7	Conclusions and future perspectives.....	706
	References.....	708

SECTION VI Polymer sustainability: Challenges, opportunities, and AI

CHAPTER 23	Challenges and opportunities in scaling up polymer recycling infrastructure	721
	<i>Ketaki Samanta, Indranil Dey and Suryasarathi Bose</i>	
1	Introduction	721
2	Overview of polymer types and their recycling challenges.....	723
2.1	Challenges in recycling specific polymers	724
3	Technological challenges in scaling up polymer recycling	725
3.1	Sorting and separation.....	725
3.2	Mechanical versus solvent-based recycling.....	728
3.3	Contamination and impurities.....	731
3.4	Inability to reprocess thermoset polymers.....	732

4	Economic and market challenges	732
4.1	Cost competitiveness	732
4.2	Market demand for recycled materials	733
4.3	Investment in infrastructure	733
5	Policy, regulatory, and institutional challenges	733
5.1	Lack of standardized regulations	733
5.2	Extended producer responsibility (EPR)	734
5.3	Public awareness and engagement	734
6	Opportunities in scaling up polymer recycling	734
6.1	Innovation in recycling technologies	734
6.2	Advances in artificial intelligence (AI) for optimizing sorting and operational efficiencies	737
6.3	Circular economy models	738
6.4	Multi-stakeholder collaboration	741
6.5	Incentivizing through policy and regulation	741
7	Case studies of successful polymer recycling models	741
7.1	Case study one	741
7.2	Case study two	744
7.3	Case study three	744
8	Future directions and conclusion	746
	References	747

CHAPTER 24 Integration of artificial intelligence in renewable polymers

recycling 755

Mariangeles Salas, Ronald Marquez and Lokendra Pal

1	Introduction	755
2	Overview of renewable polymers	758
2.1	Polylactic acid (PLA)	758
2.2	Polyhydroxyalkanoates (PHAs)	760
2.3	Bio-based polyethylene (bio-PE), polypropylene (bio-PP), and polyethylene terephthalate (bio-PET)	760
2.4	Starch-based and cellulose-based polymers	761
2.5	PBAT (Polybutylene Adipate Terephthalate)	762
3	Technical challenges and the role of artificial intelligence in renewable polymer recycling	762
3.1	Material detection and classification	762
3.2	Mechanical recycling process optimization	768
3.3	Chemical recycling pathways	769
3.4	Biological recycling and biopolymer degradation	771

4	AI as an enabler of circular polymer systems.....	772
5	Emerging directions for AI-enabled polymer circularity.....	774
6	Conclusion.....	776
	References.....	777
	Index	785

Contributors

Ricardo Abejón

Universidad de Santiago de Chile USACH, Departamento de Ingeniería Química y Bioprocesos, Santiago de Chile, Chile

Waheed Afzal

School of Engineering, University of Aberdeen, Aberdeen, Scotland

Roberto J. Aguado

LEPAMAP-PRODIS Research Group, University of Girona, Girona, Spain

Muhammad Naseem Akhtar

Interdisciplinary Research Center for Refining and Advanced Chemicals, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia; Department of Chemistry, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

Betül Aksoy

Ege University, Solar Energy Institute, Izmir, Turkey

Norah Al Favez

Interdisciplinary Research Center for Refining and Advanced Chemicals, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia

Bruno M. Ameduri

ICGM, University Montpellier, CNRS, ENSCM, Montpellier, France

Yingjun An

Research Center for Negative Emission Technologies, Kyushu University, Nishi-ku Fukuoka, Japan

Muhammad Usman Azam

School of Engineering, Cardiff University, Cardiff, United Kingdom; School of Engineering, University of Aberdeen, Aberdeen, Scotland

Susanta Banerjee

Indian Institute of Technology Kharagpur, Materials Science Centre, Kharagpur, West Bengal, India

María Blecua

CIRCE — Technology Center, Edificio Dinamiza, Zaragoza, Spain

Suryasarathi Bose

Indian Institute of Science, Department of Materials Engineering, Bangalore, Karnataka, India

R. Brito-Pereira

BCMaterials, Basque Center for Materials, Applications and Nanostructures, UPV/EHU Science Park, Leioa, Spain

Melih Soner Celiktaş

Ege University, Solar Energy Institute, Izmir, Turkey

Cecilia Chaine

CIRCE — Technology Center, Edificio Dinamiza, Zaragoza, Spain

C.M. Costa

Centre of Physics Universities of Minho and Porto and Laboratory of Physics for Materials and Emergent Technologies, LapMET, University of Minho, Campus de Gualtar, Braga, Portugal; Institute of Science and Innovation for Bio-Sustainability (IB-S), University of Minho, Braga, Portugal

P. Costa

Centre of Physics Universities of Minho and Porto and Laboratory of Physics for Materials and Emergent Technologies, LapMET, University of Minho, Campus de Gualtar, Braga, Portugal

Marc Delgado-Aguilar

LEPAMAP-PRODIS Research Group, University of Girona, Girona, Spain

Rohitha Devaraj

Industrial and Environmental Sustainability Laboratory, Department of Biotechnology, School of Bioengineering, SRM Institute of Science and Technology, Chennai, Tamil Nadu, India

Indranil Dey

Indian Institute of Science, Department of Materials Engineering, Bangalore, Karnataka, India

Eliana Díaz-Cruces

Grupo de Investigación Derecho Equidad Gobernanza y Sostenibilidad para la Justicia Social (LEGOS), Facultad de Ciencias Jurídicas, Universidad a Distancia de Madrid (UDIMA), Madrid, Spain

Etienne Fleury

INSA Lyon, Université Lyon 1, Université Jean Monnet Saint-Etienne, CNRS, IMP, UMR5223, Villeurbanne, France

Emma Franco-Mateos

CIRCE — Technology Center, Edificio Dinamiza, Zaragoza, Spain

Kazuki Fujiwara

Graduate School of Environmental Studies, Tohoku University, Sendai, Japan

Sekaran Ganesan

Industrial and Environmental Sustainability Laboratory, Department of Biotechnology, School of Bioengineering, SRM Institute of Science and Technology, Chennai, Tamil Nadu, India

Martin George Thomas

ICGM, University Montpellier, CNRS, ENSCM, Montpellier, France; Department of Physics & Electronics, CHRIST University (Deemed to be University), Bangalore, Karnataka, India

Bholanath Ghanti

Indian Institute of Technology Kharagpur, Materials Science Centre, Kharagpur, West Bengal, India

Agustín González

Universidad Nacional de Córdoba, Facultad de Ciencias Químicas, Departamento de Química Orgánica, Córdoba, Argentina; Instituto de Investigación y Desarrollo en Ingeniería de Procesos y Química Aplicada (IPQA-CONICET), Córdoba, Argentina

Inês Graça

School of Engineering, University of Aberdeen, Aberdeen, Scotland

Sanna Gull

Interdisciplinary Research Center for Sustainable Energy Systems, King Fahd University of Petroleum and Minerals (KFUPM), Saudi Arabia

Mohammad Harun-Ur-Rashid

International University of Business Agriculture and Technology (IUBAT), Department of Chemistry, Dhaka, Bangladesh

Abu Bin Imran

Bangladesh University of Engineering and Technology, Department of Chemistry, Dhaka, Bangladesh

Haru Ishikawa

Graduate School of Environmental Studies, Tohoku University, Sendai, Japan

Hasan Jameel

Department of Forest Biomaterials, North Carolina State University, Raleigh, NC, United States

Tomoko Kajiwara

Research Center for Negative Emission Technologies, Kyushu University, Nishi-ku Fukuoka, Japan

Ramani Kandasamy

Industrial and Environmental Sustainability Laboratory, Department of Biotechnology, School of Bioengineering, SRM Institute of Science and Technology, Chennai, Tamil Nadu, India

Serena Kocyan

INSA Lyon, F-69621, Villeurbanne Cedex, France

Shogo Kumagai

Graduate School of Environmental Studies, Tohoku University, Sendai, Japan; Graduate School of Engineering, Tohoku University, Sendai, Japan

Jacques Lalevée

Université de Haute-Alsace, CNRS, Mulhouse, France; Université de Strasbourg, Strasbourg, France

S. Lanceros-Méndez

Centre of Physics Universities of Minho and Porto and Laboratory of Physics for Materials and Emergent Technologies, LapMET, University of Minho, Campus de Gualtar, Braga, Portugal; BCMaterials, Basque Center for Materials, Applications and Nanostructures, UPV/EHU Science Park, Leioa, Spain; IKERBASQUE, Basque Foundation for Science, Bilbao, Spain

Pralay Maiti

School of Materials Science and Technology, Indian Institute of Technology (BHU), Varanasi, Uttar Pradesh, India

Ronald Marquez

LEPAMAP-PRODIS Research Group, University of Girona, Girona, Spain

Pablo A. Mercadal

Universidad Nacional de Córdoba, Facultad de Ciencias Químicas, Departamento de Química Orgánica, Córdoba, Argentina; Instituto de Investigación y Desarrollo en Ingeniería de Procesos y Química Aplicada (IPQA-CONICET), Córdoba, Argentina; Universidad Nacional de Córdoba, Facultad de Ciencias Agropecuarias, Departamento de Recursos Naturales, Córdoba, Argentina

Anastasia-Maria Moschovi

Monolithos Catalysts & Recycling Ltd, Athens, Greece

Gustavo Muñoz

Mississippi State University, Starkville, MS, United States

Guy Olivier Ngongang Ndjawa

Interdisciplinary Research Center for Sustainable Energy Systems, King Fahd University of Petroleum and Minerals (KFUPM), Saudi Arabia; Chemical Engineering Department, King Fahd University of Petroleum and Minerals (KFUPM), Dhahran, Saudi Arabia

Toru Nishiyama

Environmental Solution Department, DOWA Eco-System Co. Ltd., Tokyo, Japan

Pranav Omanakuttan

School of Energy Materials, School of Chemical Sciences, School of Nanoscience and Nanotechnology, International and Inter University Centre for Nanoscience and Nanotechnology, Mahatma Gandhi University, Kottayam, Kerala, India

Yasemin Ozliman

Ege University, Solar Energy Institute, Izmir, Turkey; Izmir Bakircay University, Izmir, Turkey

Adchara Padermshoke

Research Center for Negative Emission Technologies, Kyushu University, Nishi-ku Fukuoka, Japan

Lokendra Pal

Department of Forest Biomaterials, North Carolina State University, Raleigh, NC, United States

Ashwanth Pari

Industrial and Environmental Sustainability Laboratory, Department of Biotechnology, School of Bioengineering, SRM Institute of Science and Technology, Chennai, Tamil Nadu, India

Upakar Patel

School of Materials Science and Technology, Indian Institute of Technology (BHU), Varanasi, Uttar Pradesh, India

Ekaterini Polyzou

Monolithos Catalysts & Recycling Ltd, Athens, Greece

Daniel Portinha

INSA Lyon, Université Lyon 1, Université Jean Monnet Saint-Etienne, CNRS, IMP, UMR5223, Villeurbanne, France

Yuko Saito

Graduate School of Environmental Studies, Tohoku University, Sendai, Japan

Mariangeles Salas

Department of Forest Biomaterials, North Carolina State University, Raleigh, NC, United States

Ketaki Samanta

Indian Institute of Science, Department of Materials Engineering, Bangalore, Karnataka, India

Dennis W. Smith, Jr.

Mississippi State University, Starkville, MS, United States

Maxim Solovyev

Mississippi State University, Starkville, MS, United States

Sathyaprakash Sreenivasan

Industrial and Environmental Sustainability Laboratory, Department of Biotechnology, School of Bioengineering, SRM Institute of Science and Technology, Chennai, Tamil Nadu, India

Masimukku Srinivaas

Center for Environmental Toxin and Emerging-Contaminant Research, Cheng Shiu University, Kaohsiung, Taiwan

Md. Abu Bin Hasan Susan

University of Dhaka, Faculty of Science and Dhaka University Nanotechnology Center, Dhaka, Bangladesh

Atsushi Takahara

Research Center for Negative Emission Technologies, Kyushu University, Nishi-ku Fukuoka, Japan

Quim Tarres

LEPAMAP-PRODIS Research Group, University of Girona, Girona, Spain

Sabu Thomas

Department of Physics & Electronics, CHRIST University (Deemed to be University), Bangalore, Karnataka, India; Polymer and Process Engineering, IIT Roorkee, Uttarakhand, India

Muhammad Umer

Centre for Sustainable Technologies, School of Architecture and the Built Environment, Ulster University, Belfast, United Kingdom

Karmuhil Mathimozhiyazh Vetrivelan

Industrial and Environmental Sustainability Laboratory, Department of Biotechnology, School of Bioengineering, SRM Institute of Science and Technology, Chennai, Tamil Nadu, India

Iakovos Yakoumis

Monolithos Catalysts & Recycling Ltd, Athens, Greece

Kaidan Yang

Université de Haute-Alsace, CNRS, Mulhouse, France; Université de Strasbourg, Strasbourg, France

Toshiaki Yoshioka

Graduate School of Environmental Studies, Tohoku University, Sendai, Japan

Eirini Zagoraiou

Monolithos Catalysts & Recycling Ltd, Athens, Greece

Camilo Zamora-Ledezma

Bioengineering & Regenerative Medicine Research Group (Bio-ReM), Escuela de Ingeniería, Arquitectura y Diseño (EIAD), Universidad Alfonso X el Sabio (UAX), Madrid, Spain; Biomedical Research Unit (UIB-UAX), Universidad Alfonso X el Sabio (UAX), Madrid, Spain; Green and Innovative Technologies for Food, Environment and Bioengineering Research Group (FEnBeT), Faculty of Pharmacy and Nutrition, UCAM-Universidad Católica San Antonio de Murcia, Murcia, Spain

Regulatory frameworks and policies for polymer recycling

2

Eliaana Díaz-Cruces¹ and Camilo Zamora-Ledezma^{2, 3, 4}

¹*Grupo de Investigación Derecho Equidad Gobernanza y Sostenibilidad para la Justicia Social (LEGOS), Facultad de Ciencias Jurídicas, Universidad a Distancia de Madrid (UDIMA), Madrid, Spain;* ²*Bioengineering & Regenerative Medicine Research Group (Bio-ReM), Escuela de Ingeniería, Arquitectura y Diseño (EIAD), Universidad Alfonso X el Sabio (UAX), Madrid, Spain;* ³*Biomedical Research Unit (UIB-UAX), Universidad Alfonso X el Sabio (UAX), Madrid, Spain;* ⁴*Green and Innovative Technologies for Food, Environment and Bioengineering Research Group (FEnBeT), Faculty of Pharmacy and Nutrition, UCAM-Universidad Católica San Antonio de Murcia, Murcia, Spain*

1. Introduction

Plastic pollution has become one of the most persistent environmental challenges worldwide, with millions of tons of plastic waste entering natural ecosystems each year (Williams and Rangel-Buitrago, 2022). This issue not only intimidates marine and terrestrial life but also poses serious risks to human health and the stability of global food sequences (Rhodes, 2018). As a matter of fact, the extensive use of single-use plastics, combined with insufficient recycling infrastructure and waste management systems, has led to the accumulation of plastic fragments even in the most remote corners of the planet (Bergmann et al., 2022). Thus, if current trends continue, the volume of plastic waste in the oceans could surpass that of fish by 2050 (Schmaltz et al., 2020). In response to this issue, governments around the world are implementing policies such as prohibitions on single-use plastics, requirements for minimum recycled content in packaging, and extended producer responsibility schemes (Knoblauch and Mederake, 2021). These regulatory measures are inspiring manufacturers to redesign products, invest in new recycling technologies, and adopt principles of the circular economy (Bolger and Doyon, 2019). In this context, the European Union has set ambitious targets for plastic packaging recyclability and recycled content. Also, international agreements like the Basel Convention are fostering greater global cooperation in managing plastic waste (Ghosh et al., 2016). However, the success of these regulations depends on three fundamental pillars: i.- effective enforcement, ii.- industry collaboration, and iii.- public participation. It is very important to stress, that beyond those pillars, a strong regulatory framework would be essential for driving the systemic changes needed to address the global challenge of plastic waste and promote sustainable polymer recycling.