

Electronic Waste

Electronic Waste

Recycling and Reprocessing for a Sustainable Future

Edited by

Maria E. Holuszko

Amit Kumar

Denise C. R. Espinosa

WILEY-VCH

Editors

Dr. Maria E. Holuszko

The University of British Columbia
NBK Institute of Mining Engineering
517-6350 Stores Road
V6T 1Z4 Vancouver, BC
Canada

Dr. Amit Kumar

The University of British Columbia
NBK Institute of Mining Engineering
517-6350 Stores Road
V6T 1Z4 Vancouver, BC
Canada

Dr. Denise C. R. Espinosa

University of Sao Paulo
Polytechnic School, Department of
Chemical Engineering
Av. Prof. Luciano Gualberto
380 – Butantã, São Paulo, SP 05508-010
Brazil

Cover Design: Wiley

Cover Image: © Andrei Kuzmik/
Shutterstock, Recycling symbol – public
domain

■ All books published by **WILEY-VCH** are carefully produced. Nevertheless, authors, editors, and publisher do not warrant the information contained in these books, including this book, to be free of errors. Readers are advised to keep in mind that statements, data, illustrations, procedural details or other items may inadvertently be inaccurate.

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data

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

Bibliographic information published by the Deutsche Nationalbibliothek

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at <<http://dnb.d-nb.de>>.

© 2022 WILEY-VCH GmbH, Boschstr. 12,
69469 Weinheim, Germany

All rights reserved (including those of translation into other languages). No part of this book may be reproduced in any form – by photoprinting, microfilm, or any other means – nor transmitted or translated into a machine language without written permission from the publishers. Registered names, trademarks, etc. used in this book, even when not specifically marked as such, are not to be considered unprotected by law.

Print ISBN: 978-3-527-34490-1

ePDF ISBN: 978-3-527-81642-2

ePub ISBN: 978-3-527-81640-8

oBook ISBN: 978-3-527-81639-2

Typesetting Straive, Chennai, India

Printing and Binding

Printed on acid-free paper

10 9 8 7 6 5 4 3 2 1

Contents

Preface *xiii*

1	Introduction, Vision, and Opportunities	1
	<i>Maria E. Holuszko, Denise C. R. Espinosa, Tatiana Scarazzato, and Amit Kumar</i>	
1.1	Background	1
1.2	E-Waste	2
1.3	Outline	8
	References	9
2	e-Waste Management and Practices in Developed and Developing Countries	15
	<i>Pablo Dias, Andréa M. Bernardes, and Nazmul Huda</i>	
2.1	Introduction	15
2.2	Overview on WEEE Management and Practices	16
2.3	International WEEE Management and Transboundary Movement	18
2.4	WEEE Management and Practices – Developed and Developing Countries	19
2.5	Developed Countries	21
2.5.1	Switzerland	21
2.5.2	Japan	22
2.5.3	Australia	22
2.6	Developing Countries	23
2.6.1	Brazil	23
2.6.2	India	23
2.6.3	South Africa	24
2.6.4	Nigeria	25
2.6.5	Taiwan	25
2.7	Conclusions	26
	References	26

3	e-Waste Transboundary Movement Regulations in Various Jurisdictions	33
	<i>Pablo Dias, Md Tasbirul Islam, Bin Lu, Nazmul Huda, and Andréa M. Bernarde</i>	
3.1	Background	33
3.2	International Legislation and Transboundary Movement	34
3.3	Extended Producer Responsibility (EPR)	41
3.4	Regulations in Various Jurisdictions	41
3.4.1	Europe	43
3.4.1.1	France	43
3.4.1.2	Germany	43
3.4.1.3	Switzerland	44
3.4.1.4	Norway	44
3.4.2	Americas	45
3.4.2.1	United States of America	45
3.4.2.2	Canada	46
3.4.2.3	Brazil	47
3.4.3	Asia	47
3.4.3.1	Japan	47
3.4.3.2	China	48
3.4.3.3	Taiwan	49
3.4.3.4	India	49
3.4.4	Africa	49
3.4.4.1	South Africa	49
3.4.4.2	Nigeria	50
3.4.5	Australia	50
3.5	Conclusions	51
	References	52
4	Approach for Estimating e-Waste Generation	61
	<i>Amit Kumar</i>	
4.1	Background	61
4.2	Econometric Analysis	61
4.3	Consumption and Use/Leaching/Approximation 1 Method	62
4.4	The Sales/Approximation 2 Method	63
4.5	Market Supply Method	63
4.5.1	Simple Delay	63
4.5.2	Distribution Delay Method	63
4.5.3	Carnegie Mellon Method/Mass Balance Method	64
4.6	Time-Step Method	64
4.7	Summary of Estimation Methods	65
4.8	Lifespan of Electronic Products	65
4.9	Global e-Waste Estimation	66
	References	69

5	Materials Used in Electronic Equipment and Manufacturing Perspectives	73
	<i>Daniel D. München, Pablo Dias, and Hugo M. Veit</i>	
5.1	Introduction	73
5.2	Large Household Appliances (LHA)	75
5.3	Small Household Appliance (SHA)	76
5.4	IT and Telecommunications Equipment	78
5.4.1	Computers and Notebooks	78
5.4.2	Monitors and Screens	79
5.4.3	Mobile Phones (MP)	81
5.4.4	Printed Circuit Boards (PCB)	83
5.5	Photovoltaic (PV) Panels	85
5.6	Lighting Equipment	86
5.7	Toys, Leisure, and Sport	86
5.8	Future Trends in WEEE – Manufacturing, Design, and Demand	89
	References	91
6	Recycling Technologies – Physical Separation	95
	<i>Amit Kumar, Maria E. Holuszko, and Shulei Song</i>	
6.1	Introduction	95
6.2	Dismantling	96
6.3	Comminution/Size Reduction	97
6.3.1	Shredders	97
6.3.2	Hammer Mills	98
6.3.3	High-Voltage Fragmentation	98
6.3.4	Knife Mills	100
6.3.5	Cryogrinding	100
6.4	Particle Size Analysis	100
6.5	Size Separation/Classification	102
6.5.1	Screening	102
6.5.2	Classification	104
6.5.2.1	Centrifugal Classifier	104
6.5.2.2	Gravitational Classifiers	105
6.6	Magnetic Separation	106
6.6.1	Low-Intensity Magnetic Separators	106
6.6.2	High-Intensity Magnetic Separators	107
6.7	Electrical Separation	108
6.7.1	Corona Electrostatic Separation	108
6.7.2	Triboelectric Separation	109
6.7.3	Eddy Current Separation	110
6.8	Gravity Separation	111
6.8.1	Jigs	112
6.8.2	Spirals	112
6.8.3	Shaking Tables	113
6.8.4	Zig-Zag Classifiers	114

- 6.8.5 Centrifugal Concentrators 114
- 6.8.6 Dense Medium Separation (DM Bath/Cyclone) 115
- 6.9 Froth Flotation 116
- 6.10 Sensor-Based Sorting 119
- 6.11 Example Flowsheets 119
- References 123

7 Pyrometallurgical Processes for Recycling Waste Electrical and Electronic Equipment 135

Jean-Philippe Harvey, Mohamed Khalil, and Jamal Chaouki

- 7.1 Introduction 135
- 7.2 Printed Circuit Boards 136
- 7.3 Pyrometallurgical Processes 137
 - 7.3.1 Smelting 138
 - 7.3.1.1 Copper-Smelting Processes – Sulfide Route 138
 - 7.3.1.2 Copper-Smelting Processes – Secondary Smelters 142
 - 7.3.1.3 Lead-Smelting Processes 142
 - 7.3.1.4 Advantages and Limitations of Smelting Processes 146
 - 7.3.2 Electrochemical Processes 147
 - 7.3.2.1 High-Temperature Electrolysis 148
 - 7.3.2.2 Low-Temperature Electrolysis 149
 - 7.3.3 Other Pyrometallurgical Operations Used in Electronic Waste Recycling 152
 - 7.3.3.1 Roasting 152
 - 7.3.3.2 Molten Salt Oxidation Treatment 152
 - 7.3.3.3 Distillation 153
 - 7.3.3.4 Pyrolysis 155
- References 157

8 Recycling Technologies – Hydrometallurgy 165

Denise C. R. Espinosa, Rafael P. de Oliveira, and Thamiris A. G. Martins

- 8.1 Background 165
- 8.2 Waste Printed Circuit Boards (WPCBs) 167
- 8.3 Photovoltaic Modules (PV) 172
- 8.4 Batteries 176
- 8.5 Light-Emitting Diodes (LEDs) 178
- 8.6 Trends 180
- References 181

9 Recycling Technologies – Biohydrometallurgy 189

Franziska L. Lederer and Katrin Pollmann

- 9.1 Introduction 189
- 9.2 Bioleaching: Metal Winning with Microbes 189
- 9.3 Biosorption: Selective Metal Recovery from Waste Waters 191
 - 9.3.1 Biosorption Via Metal Selective Peptides 194

9.3.2	Chelators Derived from Nature	196
9.4	Bioflotation: Separation of Particles with Biological Means	197
9.5	Bioreduction and Bioaccumulation: Nanomaterials from Waste	199
9.6	Conclusion	201
	References	202

10 Processing of Nonmetal Fraction from Printed Circuit Boards and Reutilization 213

Amit Kumar and Maria E. Holuszko

10.1	Background	213
10.2	Nonmetal Fraction Composition	214
10.3	Benefits of NMF Recycling	215
10.3.1	Economic Benefits	215
10.3.2	Environmental Protection and Public Health	216
10.4	Recycling of NMF	218
10.4.1	Physical Recycling	218
10.4.1.1	Size Classification	219
10.4.1.2	Gravity Separation	219
10.4.1.3	Magnetic Separation	220
10.4.1.4	Electrical Separation	220
10.4.1.5	Froth Flotation	220
10.4.2	Chemical Recycling	221
10.5	Potential Usage	221
	References	223

11 Life Cycle Assessment of e-Waste – Waste Cellphone Recycling 231

Pengwei He, Haibo Feng, Gyan Chhipi-Shrestha, Kasun Hewage, and Rehan Sadiq

11.1	Introduction	231
11.2	Background	232
11.2.1	Theory of Life Cycle Assessment	232
11.3	LCA Studies on WEEE	234
11.3.1	Applications on WEEE Management Strategy	234
11.3.2	Applications on WEEE Management System	235
11.3.3	Applications on Hazardous Potential of WEEE Management and Recycling	236
11.4	Case Study	236
11.4.1	Goal and Scope Definition	237
11.4.1.1	Functional Unit	237
11.4.1.2	System Boundary	238
11.4.2	Life Cycle Inventory	238
11.4.2.1	Formal Collection	239
11.4.2.2	Informal Collection	239
11.4.2.3	Mechanical Dismantling	239

11.4.2.4	Plastic Recycling	240
11.4.2.5	Screen Glass Recycling	240
11.4.2.6	Battery Disposal	240
11.4.2.7	Electronic Refining for Materials	241
11.4.3	Life Cycle Impact Assessment	241
11.4.4	Results	241
11.4.4.1	Feature Phone Formal Collection Scenario	241
11.4.4.2	Feature Phone Informal Collection Scenario	243
11.4.4.3	Smartphone Formal Collection Scenario	244
11.4.4.4	Smartphone Informal Collection Scenario	246
11.4.5	Discussion	247
11.5	Conclusion	249
	References	250

12 Biodegradability and Compostability Aspects of Organic Electronic Materials and Devices 255

Abdelaziz Gouda, Manuel Reali, Alexandre Masson, Alexandra Zvezdin, Nia Byway, Denis Rho, and Clara Santato

12.1	Introduction	255
12.1.1	Technological Innovation and Waste	255
12.1.2	Eco-friendliness	257
12.1.3	Organic Electronics	257
12.1.4	Opportunities for Green Organic Electronics	258
12.2	State of the Art in Biodegradable Electronics	258
12.3	Organic Field-Effect Transistors (OFETs)	260
12.3.1	Fundamentals	260
12.3.2	Anthraquinone, Benzoquinone, and Acenequinone	262
12.3.3	Quinacridones	262
12.4	Electrochemical Energy Storage	264
12.4.1	Quinones	264
12.4.2	Dopamine	265
12.4.3	Melanins	265
12.4.4	Tannins	268
12.4.5	Lignin	269
12.5	Biodegradation in Natural and Industrial Ecosystems	269
12.5.1	Degradation and Biodegradation	270
12.5.2	Composting Process	271
12.5.3	Materials Half-Life Under Composting Conditions	274
12.5.4	Biodegradation in the Environment	275
12.6	Microbiome in Natural and Industrial Ecosystems	276
12.6.1	The Ruminant–Hay Natural Ecosystem	279
12.6.2	The Termite–Wood Natural Ecosystem	280
12.6.3	The Industrial Composter–Biowaste Ecosystem	281
12.6.3.1	Municipal Composting Facility	281
12.6.3.2	Engineered Composting Facility	282

12.6.4	Specialized Inoculant Adapted to Organic Matter	282
12.6.5	Specialized Inoculant Adapted to Heavy Metals	283
12.7	Concluding Remarks and Perspectives	284
	Acknowledgment	285
	References	285
13	Circular Economy in Electronics and the Future of e-Waste	299
	<i>Nani Pajunen and Maria E. Holuszko</i>	
13.1	Introduction	299
13.2	Digitalization and the Need for Electronic Devices	301
13.3	Recycling and Circular Economy	302
13.4	Challenges for e-Waste Recycling and Circular Economy	304
13.5	Drivers for Change – Circular Economy	306
13.6	Demand for Recyclable Products	309
13.7	Summary	310
	References	312
	Index	315

Preface

Digitalization has played an essential role in social and technological development globally, while electronic and electrical equipment has become integral to our everyday lives. Digital devices provide broad access to education, instant information, continuous entertainment and contribute to mass communication, thus improving the overall quality of our lives. During the COVID-19 pandemic, the internet allowed us to function and remain a productive society worldwide.

Meanwhile, the life expectancy of most electronic devices, specifically small devices such as cellphones, tablets, and laptops, is getting shorter and shorter, resulting in alarming amounts of e-waste generation. Many discarded electronics are being improperly disposed of, hence posing a significant risk to the environment and human health. With an estimated annual growth of 3–4%, electronic waste is the fastest growing waste stream worldwide, exceeding 50 Mt annually in 2019, while only 20% of the e-waste is collected and recycled globally. The electronic devices have been reported to contain gold and copper grades, significantly exceeding the grades of many operating mines. The existence of precious metals in e-waste provides an economic incentive for recycling. On the other hand, the presence of hazardous substances in e-waste calls for complex reprocessing to decontaminate before its final disposal.

The development of efficient e-waste recycling methods and the recovery of precious metals and critical materials from e-waste are interesting and technically challenging. Furthermore, the informal urban mining of e-waste creates significant social and public health issues. Therefore, there was a need for a comprehensive overview of the current situation with e-waste generation, disposal, regulations, recycling technologies while providing a global perspective.

This book aims to overview the current global situation regarding e-waste, including technological issues with e-waste recycling and recovery of value from e-waste streams. The chapters in this book outline the definition of electronic waste, explore methods for e-waste estimation, identify challenges related to the timely information on e-waste collection and management, and elaborate on the practices in developed and developing countries. The book delivers information on currently used recycling technologies, including physical separation technologies, pyrometallurgy, hydrometallurgy, and biohydrometallurgy, and reviews materials used in the manufacturing of electronics as well as the development of new

materials for green-ecological and biodegradable electronics. Additionally, methods and ideas for new practices to facilitate sustainability in the electronics industry are proposed to “close the loop” in industrial production to minimize waste generation and possibly to promote a zero-waste scenario. The book concludes with a chapter on the circular economy in electronics and provides some perspective on the future of electronic waste.

This book was made possible through collaboration between international experts in the field of e-waste recycling. It collates academic and industrial expertise to provide a comprehensive overview of the scope of the problem with electronics worldwide, specifically on their fate as e-waste and the recycling efforts to shed light on the current e-waste paradigm.

Vancouver, July 2021

Maria E. Holuszko
Amit Kumar
Denise C. R. Espinosa