Norbert Niessner (Ed.)

Recycling of Plastics

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Preface

Plastics have offered and still offer an unprecedented step-up in quality of life. Their beneficial effects range from reduction of food waste by extension of shelf life, affordable healthcare measures through mass production of diagnostics or infusion kits, significant carbon dioxide savings through lightweight applications in automotive and aircraft, up to a wide range of electronic gadgets in lightweight yet stiff and tough protective housings. A replacement or even no-plastics strategy would not only affect lifestyle, but also increase the emission of greenhouse gases such as carbon dioxide significantly.

At the same time it is clear that environmental pollution by plastic parts must not continue as it has done until now. While recovery of precious metals – even from landfills – is already in place in many parts of the world, it is about time to treat plastic items at the end of their normal lifecycle not as waste anymore, but as a source of precious raw materials. Plastics are not the problem, but rather insufficient collection schemes and recycling initiatives.

This book intends to show the state of the art in plastics recycling, the value chains, the challenges, and the solutions. The following paragraphs give a very condensed overview of the contributions and their authors (those who (co)wrote more than one contribution are mentioned just once here – see the table of contents or “The Authors” for a more complete survey).

We introduce structure-property relationships in plastics with a contribution by leading polymer scientists from Bayreuth University (Prof. Hans-Werner Schmidt Tristan Kolb, and Andreas Schedl), will touch the economics and deep-dive into the important topics of legislation and political/legal boundaries, contributed by two major stakeholders in this field (Accenture with Michael Ulbrich, Marvin Stiefermann, and Sören Hörnicke, and BASF SE with Klaus Wittstock and Victoria Wessolowski). By this dual approach we emphasize the overarching importance of politics and legislation for the successful, global implementation of plastics recycling.

LCA contributions by BASF SE (Prof. Peter Saling), NMB (Thomas Neumeyer, Regino Weber), and TU Braunschweig (Prof. Stephan Scholl, Mandy Paschetag, and Hannes Schneider) complete the first part (Part A).

The recycling chapters will be introduced by Prof. Christian Hopmann, Prof. Rainer Dahlmann, and Martin Facklam (IKV Aachen), followed by a split into mechanical and advanced recycling (by chemistry-based measures), including contributions by Prof. Achim Schmiemann (IFR); Marco Amici (INEOS O&P); Prof. Thomas Schröder (ikd Darmstadt); Hermann van Roost (SCS Brussels); Eike Jahnke and Bianca Wilhelmus (INEOS Styrolution); Hannah Mangold and Caroline Beyer (BASF); Jason Leadbitter (INEOS INOVYN); Prof. Dieter Stapf (KIT); Prof. Thorsten Gerdes, Achim Schmidt-Rodenkirchen, Stephan Aschauer, and Klaus Hintzer (InVerTec); Adrian Griffiths, Stephanie Loo, and Alejandro Sánchez (Recycling Technologies);

and Carsten Eichert and Vitalij Salikov (Rittec). A section on the dissolution technology is provided by the Fraunhofer Freising team around Andreas Mäurer and Martin Schlummer.

Contributions by two key representatives from the recycling and sorting industry – by Jürgen Ephan and Arne Köhne (REMONDIS) and Jürgen Priesters (TOMRA) – complement the view on the value chain, introduced by Raphael Kiesel.

We conclude our book with contributions on reuse examples, design for recycling, and future developments from Prof. Volker Altstädt, Prof. Holger Ruckdäschel, Tobias Standau, Matthias Mühlbacher, Josefa Nüßlein, Robin Fachtan (NMB), and Eric Homey.

Our book is written for the decision makers in companies, public institutions, and government/administration, for the student, as well as for the experts from academia and industry. We hope that all stakeholders will receive a comprehensive overview, allowing the identification of the best solution for each recycling challenge.

Norbert Niessner, Editor August 2022

Foreword

Recycling of plastics is a very important topic for society, policymakers, and industry.

Plastic is a material we use every day. It helps feed the world sustainably, keeps us warm, allows us to get from A to B, and even saves lives. We cannot achieve our climate ambitions without plastics.

But we also know that plastics, plastics production and plastics waste management must be sustainable.

To transition to the EU's net zero emissions goals by 2050 requires the European plastics system to realize drastic emissions reductions across the entirety of the value chain, from raw materials to end-of-life. The stakes are high as we know societal sustainability goals, triggered by new EU legislation and consumer/citizen demand, are not just confined to Europe but impact global trade systems too.

Circularity is absolutely fundamental to our industry's transition. It is the most important medium-term lever and recycling is an essential component of circularity. "Reshaping Plastics", an independent report commissioned by Plastics Europe in 2022, concluded that by 2050 the plastics system could achieve 78% circularity with 48% being recycled.

Plastics Europe and our members recognize systemic change is essential to achieve this and needs to be accelerated. European plastics manufacturers are already undertaking huge investments and a far-reaching reorganization of their production and technology base to increase circularity and support recycling.

But we are under no illusions about the scale and complexity of this transition. The European plastics system is extremely diverse and complex. We are talking about multiple supply chains, delivering thousands of products and a plethora of industrial and consumer applications. There is no silver bullet solution.

Whilst plastics manufacturers have a very important role to play in supporting the transition to net zero, we represent only one part of the European plastics system. We do not have all the answers or levers to the recycling challenges we and the plastics system face and cannot do it alone.

Policymakers also have a vital role to play. Accelerating the transition requires an enabling policy framework that incentivizes and fosters a climate of creative collaboration and competition. One that helps to maximize investment and innovation from both private and public actors.

Deeper collaboration between the plastics industry, value chain, policy makers, increased investment and innovation – all of this is vital and it has to be based on a deeper and science-based understanding of the challenges and opportunities that we face in relation to recycling. This is why I welcome this book.

Packed with vital insights and detailed analysis, “Recycling of Plastics” is an invaluable resource for all of us as we rise to the collective challenge and opportunity of creating a circular plastics economy.

Happy reading!

Virginia Janssens

Plastics Europe – Managing Director

Foreword 2

Plastics are ubiquitous in our everyday lives. Economically, they are one of the most prolific materials, with above average global growth rates surpassing other key materials such as paper, glass, or aluminum.

This is not least due to the remarkable properties of plastics, which bring many benefits to the individual consumer as well as society as a whole. For example, plastics are used in packaging to protect goods, also helping to reduce food waste, and to build lighter and more fuel-efficient vehicles, helping to reduce greenhouse gas emissions.

However, more recently, the focus of the public perception of plastics has shifted towards their end of life. Globally, only a small portion of plastic waste is collected, sorted, and recycled, while too much of it is still incinerated, landfilled, or, even worse, leaked into the environment. Policymakers, NGOs, plastic users and end consumers, as well as investors increasingly demand that the plastics industry accepts its share of responsibility and takes concrete action against plastic pollution and greenhouse gas emissions by transitioning from a linear to a circular economy.

Indeed, circularity is an integral aspect of sustainability. Implementing "reduce, reuse, and recycle" (3R) is one key approach to addressing the urgent need to mitigate climate change, in line with the Paris Agreement at a global level, as well as, more specifically, the European Green Deal and the Circular Economy Action Plan (CEAP) at the European Union (EU) level. Our common goal must be a circular, net-zero carbon plastics economy. In the end, further increasing collection, sorting, and recycling of plastic waste will be instrumental to achieve this, in addition to reuse models and renewable materials. This includes standardizing and designing plastic products to increase their ability to be recycled and incorporate recycled content, with closed-loop systems as the ultimate goal, where they are the most sustainable solution.

Also in support of fact-based policy and other decision making, industry will continue to contribute to meeting expectations regarding transparency. This includes aspects such as data collection, traceability, monitoring, and accountability, as well as providing comprehensive scientific evidence on the life cycle impacts of its products.

The global transition to a sustainable, circular economy cannot be achieved with isolated solutions. Within an enabling policy framework, cooperation along the value chains is key to achieve these objectives. In the EU, the Circular Plastics Alliance (CPA) and polymer value chain associations such as PETCORE (PET), PCEP (PE, PP), Vinylplus (PVC), and SCS (Styrenics) are visible examples of such cooperation.

This book provides a strong fact base for all stakeholders involved or interested in the circular economy for plastic. To help to better understand feasibilities, limitations, and opportunities, it lays out the potential of existing mid- and long-term solutions, enabling conditions, as well as trends and future developments. This includes standardization and the huge but not yet fully tapped potential of design for recycling.

Against the backdrop of the above-mentioned as well as more recent developments, the release of this book is timely, as it presents a technology roadmap and possible choices regarding circular feedstocks, which will also help to meet the urgent strategic needs to save fossil resources such as crude oil and natural gas.

I hope that with its diverse content and contributing authors, this book may inspire all its readers to closely communicate and collaborate with each other. With commitment, concrete action, and solutions, together we can deliver an answer to the dual challenge of climate change and plastics pollution by realizing the circular economy for plastics.

Jens Kathmann

Secretary General, Styrenics Circular Solutions (SCS)

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The Editor

Norbert Niessner

Dr. Norbert Niessner is Innovation Director at INEOS Styrolution. He is a Chemistry graduate from Marburg University, Germany, at which he also obtained his PhD in Polymer Chemistry. From 1989 to 1990, he worked as a post-doctoral fellow at IBM Almaden Research Labs in San Jose, California. After joining BASF in 1990, he held several positions in R&D and marketing & sales in Europe, as well as in Asia. In 2011, he joined the newly created BASF/INEOS joint venture “Styrolution”, now a 100% INEOS company.

During his career, Dr. Niessner gained experience in building and leading global R&D and business management teams in the polymers industry worldwide, with focus Europe and Asia. In terms of patents/applications, he is one of the leading inventors in styrenic polymers. His publication/patent list comprises more than 300 tech/scientific papers, book chapters, and original inventions. Special fields of interest are, amongst others, liquid crystalline polymers, development of world-scale polymer manufacturing technologies and product lines, polymers for 3D printing, and advanced recycling technologies.

The Coauthors

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2	Introduction to Major Thermoplastic Polymers in the Context of Recycling	▪ Dr. Tristan Kolb, Neue Materialien Bayreuth GmbH, Bayreuth

		▪ Andreas Schedl, Neue Materialien Bayreuth GmbH, Bayreuth ▪ Prof. Hans-Werner Schmidt, University of Bayreuth
3	Legislation	▪ Michael Ulbrich ▪ Sören Hörnicke Accenture GmbH, Kronberg im Taunus
4	Economics	▪ Michael Ulbrich ▪ Dr. Marvin Stiefermann Accenture GmbH, Kronberg im Taunus
5	Political Boundary Conditions – Plastics Waste Management	▪ Dr. Klaus Wittstock

		▪ Victoria Wessolowski BASF SE, Ludwigshafen am Rhein
6.1	Introduction: What Is Life Cycle Assessment?	▪ Prof. Dr. Peter Saling, BASF SE, Ludwigshafen am Rhein
6.2	Life Cycle Assessment for Different Recycling Routes of Polystyrene	▪ Regino Weber ▪ Dr.-Ing. Thomas Neumeyer Neue Materialien Bayreuth GmbH, Bayreuth
6.3	Life Cycle Assessment of a New Monomer Recycling Process for PET	▪ Dr.-Ing. Mandy Paschetag ▪ Hannes Schneider ▪ Prof. Dr.-Ing. Stephan Scholl Technische Universität

		Braunschweig
7	Overview of Major Recycling Technologies	▪ Prof. Dr.-Ing. Christian Hopmann ▪ Prof. Dr. rer. nat. Rainer Dahlmann ▪ Dr.-Ing Martin Facklam Institute for Plastics Processing (IKV) in Industry and Craft at RWTH Aachen University
8.1	Basic Principles	▪ Prof. Dr.-Ing. Achim Schmiemann, Ostfalia University of Applied Sciences, Wolfsburg
8.2	Mechanical Recycling of Polyolefins	▪ Dr. Marco Amici, INEOS Olefins and Polymers Europe, Rolle

8.3	Mechanical Recycling of PET	▪ Prof. Dr.-Ing. Thomas Schröder, Darmstadt University of Applied Sciences
8.4.1	Mechanical Recycling of Polystyrene	▪ Herman Van Roost, Styrenics Circular Solutions, Brussels
8.4.2	Mechanical Recycling of Styrene Copolymers	▪ Dr. Eike Jahnke, INEOS Styrolution Europe GmbH, Frankfurt am Main
8.5	Mechanical Recycling of Engineering Thermoplastics	▪ Dr. Hannah Mangold ▪ Dr. Caroline Beyer BASF SE, Ludwigshafen am Rhein

8.6	Mechanical Recycling of PVC	▪ Dr. Jason Leadbitter, INEOS INOVYN, Newton Aycliffe
8.7	Compatibilization of Blends for Mechanical Recycling	▪ Dr. Norbert Nießner ▪ Dr. Bianca Wilhelmus INEOS Styrolution Group GmbH, Frankfurt am Main
9.1.1	An Overview of Major Recycling Technologies	▪ Dr. Bianca Wilhelmus, INEOS Styrolution Group GmbH, Frankfurt am Main
9.1.2	Petrochemical Feedstock Recycling	▪ Prof. Dr.-Ing. Dieter Stapf, Karlsruhe Institute of Technology
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15	Recycling Value Chain	▪ Jürgen

	and Detection/Purification Technologies	Priesters, TOMRA Sorting GmbH, Mülheim-Kärlich
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		▪ Tobias Standau, University of Bayreuth
19	Future Developments	▪ Prof. Dr.-Ing. Achim Schmiemann ▪ Eric Homey Ostfalia University of Applied Sciences, Wolfsburg

* Order according to chapter/section number.

Glossary

AA	Acrylic acid
ABS	Acrylonitrile–butadiene–styrene copolymer
AN	Acrylonitrile
API	A measure of how heavy or light a petroleum liquid is compared to water: if API > 10, then the liquid is lighter and floats on water; if API < 10, it is heavier and sinks
APC	Aliphatic polycarbonates
ASR	Automotive shredder residue
ASTM	American Society for Testing and Materials; international standardization organization
BGL	British Gas Lurgi Process
BHET	Bis(2-hydroxyethyl) terephthalate

BHETA	Bis(2-hydroxyethylene) terephthalamide
BMBF	German Ministry of Education and Research
BMC	Bulk molding compound
BPA	Bisphenol-A (monomer for polycarbonate)
BTX	Benzene, toluene, xylenes fraction
CAPEX	Capital expenditure
CEAP	EU Circular Economy Action Plan
CEFIC	European Chemical Industry Council
CFC	Carbon fiber composites
CFF	Circular footprint formula
Citeo	Non-profit company founded from the merger of Eco-Emballages and Ecofolio
CO_2e	Carbon dioxide equivalents
CPA	Circular Plastics Alliance of EU Commission
CPE	Chlorinated Polyethylene
CPO	Circular Polyolefins Project
CSS	EU Chemicals Strategy for Sustainability

CW	Commercial waste / consumer waste[1]
DEHP	Diethyl hexyl phthalate (plasticizer)
DfR	Design for recycling
DfS	Design for sustainability
DMT	Dimethyl terephthalate
DSC	Differential scanning calorimetry
DSD	Duales System Deutschland – German collection system
DSP	Selective dissolution and precipitation
ECHA	European Chemicals Agency
ED	Endocrine disruptor
EEA	Eco efficiency analysis
EfW	Energy from Waste
EG	Ethylene glycol
EGMA	Ethylene–glycidyl methacrylate
EHS	Environment, health, safety
EHS&S	Environment, health, safety, and sustainability

ElektroG	German Electrical and Electronic Equipment Act
ELV	End-of-life vehicle
EPA	U.S. Environmental Protection Agency
EPC	Engineering, procurement, construction
EPDM	Ethylene–propylene–diene terpolymer
EPM	Poly(ethylene-co-propylene)
EPR	Extended producer responsibility
EPS	Expanded polystyrene
ETICS	External Thermal Insulation Composite System
EVA	Ethylene–vinyl acetal copolymer
EVOH	Ethylene–vinyl alcohol copolymer
FBP	Final boiling point of a distillation fraction
FBR	Fluid-bed or fluidized-bed reactor
FDA	US Food and Drug Administration
FEP	Freshwater eutrophication potential
FFF	Fused filament fabrication, a 3D printing technology

GewAbfV	German industrial waste ordinance
GHG	Greenhouse gas
GMA	Glycidyl methacrylate
GWP	Global warming potential
GPPS	General purpose polystyrene
Green Dot	German dual system of waste collection (“Grüner Punkt”)
HALS	Hindered amine light stabilizer (UV stabilization additives)
HBCDD	Hexabromocyclododecane (flame retardant)
HCFC	Hydrochlorofluorocarbon
HDPE	High-density polyethylene
HEMA	Hydroxyethyl methacrylate
HIPS	High-impact polystyrene
HSP	Hansen Solubility Parameter
HTW	High-temperature Winkler process
IBP	Initial boiling point for a distillation fraction
ISO	International Organization for Standardization