The Handbook of Environmental Chemistry 63
Series Editors: Damià Barceló · Andrey G. Kostianoy

Roman Maletz
Christina Dornack
Lou Ziyang *Editors*

Source Separation and Recycling

Implementation and Benefits for a Circular Economy

Springer

The Handbook of Environmental Chemistry

Founded by Otto Hutzinger

Editors-in-Chief: Damià Barceló • Andrey G. Kostianoy

Volume 63

Advisory Board:
Jacob de Boer, Philippe Garrigues, Ji-Dong Gu,
Kevin C. Jones, Thomas P. Knepper, Alice Newton,
Donald L. Sparks

More information about this series at http://www.springer.com/series/698

Source Separation and Recycling

Implementation and Benefits for a Circular Economy

Volume Editors: Roman Maletz · Christina Dornack · Lou Ziyang

With contributions by

M. Althaus · B. Bilitewski · C. Bofeng · A. Clausen · C. Dornack · A. Elnaas · K. Fricke · H. Friege · S. Hemidat · C. Heußner · A. Hüttner · A. Lemke · H. Li · W.H. Li · Y. Long · R. Maletz · A. Nassour · M. Nelles · D. Niu · T. Pretz · P. Quicker · S. Salhofer · D. Schingnitz · D. Shen · F.-G. Simon · Y.J. Sun · Z. Tiantao · T. Turk · C. Wünsch · F. Xia · C. Zeng · Y. Zhao · C. Zhaowen · X. Zhilin · L. Ziyang

Springer

Editors
Roman Maletz
Institute of Waste Management
and Circular Economy
Technische Universität Dresden
Pirna, Germany

Christina Dornack
Institute of Waste Management
and Circular Economy
Technische Universität Dresden
Pirna, Germany

Lou Ziyang
School of Environmental Science
and Engineering
Shanghai Jiao Tong University
Shanghai, China

ISSN 1867-979X ISSN 1616-864X (electronic)
The Handbook of Environmental Chemistry
ISBN 978-3-319-69071-1 ISBN 978-3-319-69072-8 (eBook)
https://doi.org/10.1007/978-3-319-69072-8

Library of Congress Control Number: 2017961122

© Springer International Publishing AG 2018
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Editors-in-Chief

Prof. Dr. Damià Barceló

Department of Environmental Chemistry
IDAEA-CSIC
C/Jordi Girona 18–26
08034 Barcelona, Spain
and
Catalan Institute for Water Research (ICRA)
H20 Building
Scientific and Technological Park of the University of Girona
Emili Grahit, 101
17003 Girona, Spain
dbcqam@cid.csic.es

Prof. Dr. Andrey G. Kostianoy

P.P. Shirshov Institute of Oceanology
Russian Academy of Sciences
36, Nakhimovsky Pr.
117997 Moscow, Russia
kostianoy@gmail.com

Advisory Board

Prof. Dr. Jacob de Boer

IVM, Vrije Universiteit Amsterdam, The Netherlands

Prof. Dr. Philippe Garrigues

University of Bordeaux, France

Prof. Dr. Ji-Dong Gu

The University of Hong Kong, China

Prof. Dr. Kevin C. Jones

University of Lancaster, United Kingdom

Prof. Dr. Thomas P. Knepper

University of Applied Science, Fresenius, Idstein, Germany

Prof. Dr. Alice Newton

University of Algarve, Faro, Portugal

Prof. Dr. Donald L. Sparks

Plant and Soil Sciences, University of Delaware, USA

The Handbook of Environmental Chemistry Also Available Electronically

The Handbook of Environmental Chemistry is included in Springer's eBook package *Earth and Environmental Science*. If a library does not opt for the whole package, the book series may be bought on a subscription basis.

For all customers who have a standing order to the print version of *The Handbook of Environmental Chemistry*, we offer free access to the electronic volumes of the Series published in the current year via SpringerLink. If you do not have access, you can still view the table of contents of each volume and the abstract of each article on SpringerLink (www.springerlink.com/content/110354/).

You will find information about the

- Editorial Board
- Aims and Scope
- Instructions for Authors
- Sample Contribution

at springer.com (www.springer.com/series/698).

All figures submitted in color are published in full color in the electronic version on SpringerLink.

Aims and Scope

Since 1980, *The Handbook of Environmental Chemistry* has provided sound and solid knowledge about environmental topics from a chemical perspective. Presenting a wide spectrum of viewpoints and approaches, the series now covers topics such as local and global changes of natural environment and climate; anthropogenic impact on the environment; water, air and soil pollution; remediation and waste characterization; environmental contaminants; biogeochemistry; geo-ecology; chemical reactions and processes; chemical and biological transformations as well as physical transport of chemicals in the environment; or environmental modeling. A particular focus of the series lies on methodological advances in environmental analytical chemistry.

Series Preface

With remarkable vision, Prof. Otto Hutzinger initiated *The Handbook of Environmental Chemistry* in 1980 and became the founding Editor-in-Chief. At that time, environmental chemistry was an emerging field, aiming at a complete description of the Earth's environment, encompassing the physical, chemical, biological, and geological transformations of chemical substances occurring on a local as well as a global scale. Environmental chemistry was intended to provide an account of the impact of man's activities on the natural environment by describing observed changes.

While a considerable amount of knowledge has been accumulated over the last three decades, as reflected in the more than 70 volumes of *The Handbook of Environmental Chemistry*, there are still many scientific and policy challenges ahead due to the complexity and interdisciplinary nature of the field. The series will therefore continue to provide compilations of current knowledge. Contributions are written by leading experts with practical experience in their fields. *The Handbook of Environmental Chemistry* grows with the increases in our scientific understanding, and provides a valuable source not only for scientists but also for environmental managers and decision-makers. Today, the series covers a broad range of environmental topics from a chemical perspective, including methodological advances in environmental analytical chemistry.

In recent years, there has been a growing tendency to include subject matter of societal relevance in the broad view of environmental chemistry. Topics include life cycle analysis, environmental management, sustainable development, and socio-economic, legal and even political problems, among others. While these topics are of great importance for the development and acceptance of *The Handbook of Environmental Chemistry*, the publisher and Editors-in-Chief have decided to keep the handbook essentially a source of information on "hard sciences" with a particular emphasis on chemistry, but also covering biology, geology, hydrology and engineering as applied to environmental sciences.

The volumes of the series are written at an advanced level, addressing the needs of both researchers and graduate students, as well as of people outside the field of "pure" chemistry, including those in industry, business, government, research establishments, and public interest groups. It would be very satisfying to see these volumes used as a basis for graduate courses in environmental chemistry. With its high standards of scientific quality and clarity, *The Handbook of Environmental Chemistry* provides a solid basis from which scientists can share their knowledge on the different aspects of environmental problems, presenting a wide spectrum of viewpoints and approaches.

The Handbook of Environmental Chemistry is available both in print and online via www.springerlink.com/content/110354/. Articles are published online as soon as they have been approved for publication. Authors, Volume Editors and Editors-in-Chief are rewarded by the broad acceptance of *The Handbook of Environmental Chemistry* by the scientific community, from whom suggestions for new topics to the Editors-in-Chief are always very welcome.

Damià Barceló
Andrey G. Kostianoy
Editors-in-Chief

Foreword

The material we call waste today has become waste not because it has no further use but mainly due to the poor resource management practices we continue to follow. We take materials from the nature to make commodities for our consumption. Ideally, the leftovers from this process of consumption should be able to follow its natural path to return to its due place in nature. For various reasons the current waste management practices have not been able to comply with the simple demands of the natural cycle. Source separation (waste separated at the source) is one helpful step that can move us toward this natural cycle. On one hand source separation helps us realize the potential in material recovery and resource use efficiency. On the other hand it provides economic benefits. This combination provides the blueprint toward a circular economy, a concept that we all wish to see in its full swing.

Resource recovery is an essential part of the Nexus Approach that is being promoted by the UNU-FLORES. We specifically promote the integrated management of water, soil, and waste. These three resources are closely related to each other and hence they can benefit from each other through integrated management. Wastewater is a good example. Use of wastewater in agriculture not only alleviates water demand issues but also becomes a partial solution to fertilizer needs, if managed properly and safely. Making compost out of food and yard waste is another positive example for the benefits of integrated management.

In this context UNU-FLORES sees the launch of this new book on *Source Separation and Recycling: Implementation and Benefits for a Circular Economy* as a very timely and appropriate contribution. It will certainly provide more food for thought to enrich the ongoing discussions. We offer our sincere appreciation and best wishes to our colleagues Roman Maletz and Christina Dornack from TU Dresden and their partner Lou Ziyang from the Shanghai Jiao Tong University for editing this very interesting book.

UNU-FLORES
Dresden, Germany

Reza Ardakanian

Preface

Today's governments are facing increasing problems caused by rapidly growing amounts and forms of solid and hazardous wastes due to continuous economic improvement, industrialization, and urbanization. Inappropriate handling of waste leads to threats to the environment, such as greenhouse gas emissions, land degradation, water and resource pollution, and other issues. Waste disposal and resource depletion are two of the most urgent problems facing human society, and waste reduction and recycling are two promising solutions on the way to a circular economy.

In 2016, the Sino-German workshop on "Waste Reduction and Recycling: Challenges and Trends for Source Separation" was jointly organized by Shanghai Jiao Tong University and Technische Universität Dresden with the support of the Sino-German Center for Research Promotion (SGC). Participants from both sides discussed various aspects of waste reduction and recycling opportunities. The conclusions of this symposium are summarized in this book and consider some additional aspects. The focus is on the situation in China and Germany, but the results are applicable to different situations and regions in the world.

The book is sectioned into four parts, and the first part contains policy aspects and legislational drivers for the implementation of modern waste collection schemes. In the second part, segregation technologies are introduced that consider different examples from China and Germany. Before looking into the future of source separation in the world, contained in the last part, climate protection results are presented in the third part.

With this book, we hope to make the interest groups involved all over the world aware of the challenges and opportunities source separation can provide. And this book is another small step in supporting the paradigm shift from seeing the increasing residual material streams not as waste, but as valuable material in another entropic state. We wish the book widespread dissemination, and that it is of interest to the scientific community.

Naturally, we want to express our deep gratitude to all the contributing authors who offered some of their valuable time for this book.

Shanghai, China — Lou Ziyang
Pirna, Germany — Christina Dornack
Pirna, Germany — Roman Maletz

Contents

Part I
Legislational Drivers and Other Incentives for Waste Separation

Waste Policy for Source Separation in Germany

Christina Dornack

Abstract There is global consensus for developing a circular economy and building green societies. As the two leading countries in their regions in this field, both China and Germany want to reduce the environmental impacts of waste and avoid the programme of "NIMBY" and have accumulated much experience in waste reduction and gradient utilisation of waste. "Pay As You Throw", "Green Dot" system and "trade in policy (the new for old policy)" have all proven to lead to higher recycling rates and the minimisation of waste in the past 30–40 years. The article shows how German waste legislation developed to achieve the actual recycling rates. Though Germany follows the European laws, above this it has set a number of even stricter requirements, which are summarised in this paper. The main strategies for implementing source separation are described, while potentials are detected for certain waste fractions like plastics and textiles.

Keywords Circular Economy Act, Recycling rates, Source separation, Waste legislation, Waste policy

Contents

C. Dornack (✉)
Institute of Waste Management and Circular Economy, Technische Universität Dresden, Dresden, Germany
e-mail: christina.dornack@tu-dresden.de

R. Maletz et al. (eds.), *Source Separation and Recycling*, Hdb Env Chem (2018) 63: 3–10, DOI 10.1007/698_2017_114,

© Springer International Publishing AG 2017, Published online: 14 October 2017

1 Introduction: Situation in Germany

German industries have shouldered the voluntary commitment for conserving resources and avoiding waste, reinforced by obligations for returning and recovering recyclables such as glass, packaging material, metals, etc.

From 1992 to 2004, there was average economic growth of 15%. Besides that, the total volume of domestic waste remained basically the same. The recovery of municipal waste had been increased to 63% up until 2013 (Table 1). German industries have shouldered the voluntary commitment for conserving resources and avoiding waste, reinforced by obligations for returning and recovering recyclables.

As for end-of-life vehicles, batteries and electrical wastes, states are obligated to separately collect and recover containing toxic substances. In Germany, municipal waste has been defined as, “waste from private households and similar institutions, as well as domestic-type waste produced by trade and industry.”

The current situation of waste management in Germany can be summarised in three phases: “return and recovery”, “waste management” and “waste disposal.” German industries have shouldered the voluntary commitment for conserving resources and avoiding waste, reinforced by obligations for returning and recovering recyclables such as glass, packaging material, metals, etc. As for end-of-life vehicles, batteries and electrical wastes that contain toxic substances, states are obligated to collect and recover them separately. In Germany, municipal waste has been defined as “waste from private households and similar institutions, as well as domestic-type waste produced by trade and industry.” Municipal waste includes household waste, separately collected recoverable materials such as glass and paper, packaging waste, organic waste and bulky waste (Fig. 1).

2 Legal Principles of the EU and Germany

In Germany, the Circular Economy Act was installed within the last few years. The EU Waste Directive 2008/98/EC [2] sets the basic concepts and definitions related to waste management, such as definitions of waste, recycling and recovery.

Table 1 Collection of valuables in the years 1990–2014 [1]

Year	Valuables	Residual waste
1990	5 Mio. Mg, 13%	34 Mio. Mg, 87%
2004	25 Mio. Mg, 58%	18 Mio. Mg, 42%
2008	26 Mio. Mg, 61%	17 Mio. Mg, 39%
2014	29 Mio. Mg, 63%	16 Mio. Mg, 37%

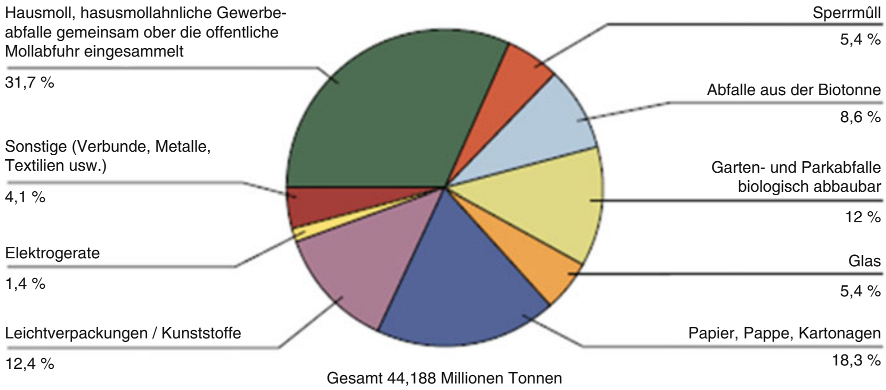

Fig. 1 Waste composition in 2015, derived from DESTATIS [1]

Furthermore, the directive explains when waste ceases to be waste and becomes a secondary raw material (so-called end-of-waste criteria) and how to distinguish between waste and by-products. The directive lays down basic waste management principles by preventing or reducing the adverse impacts of the generation and management of waste and by reducing the overall impacts of resource use and improving the efficiency of such use. In addition, it requires that waste has to be managed without endangering human health and harming the environment.

Most of the single requirements from the WFD [2] have been transposed "one to one" into national legal requirements and are hence included in the German Circular Economy Act [3].

The directive stipulates that waste legislation and policy of the EU member states shall apply as a priority order in the following waste management hierarchy:

1. *Reduce*: Reduction is the best way to manage solid waste and encompasses all manufacturing aspects such that waste is not created or is kept to a minimum by the waste producer – closely tied to the producer and to the consumer.
2. *Reuse*: Reuse is the better way to manage solid waste and will usually represent an environmental gain – in most cases it will use far less energy than recycling.
3. *Recycle*: Recycling is a good way to manage solid waste and keep items out of landfills and conserve natural resources. The goal of every recycling process is to use or reuse materials from garbage in order to minimise the amount of solid waste. Options include separation, mechanical and thermal treatment.
4. *Recovery*: Recovery includes processes like anaerobic digestion and incineration with energy recovery and other processes which produce energy and also some backfilling operations.
5. *Disposal*: Disposal means processes to dispose of waste without energy recovery such as landfilling and incineration.

2.1 Waste Avoidance

The principle of producer responsibility is embedded in the EU legislation. The Circular Economy Act includes regulations for product responsibility (§§23 ff., [3]) for the further development of the Packaging Ordinance to a uniform household-oriented recycling of valuables.

Caused by the need for the increase in resource efficiency, instruments of waste avoidance will be developed dynamically and continuously. Waste avoidance programmes are to be drawn up. Waste prevention targets need to be formulated; existing waste prevention measures will be compiled and evaluated. By that, new measures have to be developed. This is intended to strengthen waste prevention policies and make them more transparent to the public.

2.2 Improve Resource Efficiency

In order to improve resource efficiency, some additional requirements are defined in the German Circular Economy Act.

The following paragraphs in the Circular Economy Act [3] show the additional requirements:

2.2.1 §11 Recycling for Biodegradable Waste and Sewage Sludge

1. Biodegradable waste has to be collected separately, beginning with the 1 January 2015.

2.2.2 §14 Promotion of Recycling and Material Recovery

1. For the purpose of proper, safe and high-quality recycling, paper, metal, plastics and glass wastes are to be collected separately from 1 January 2015 at the latest, as far as is technically and economically practicable.
2. Preparation for the reuse and recycling of municipal solid waste is expected to total 65% w/w on 1 January 2020.
3. For construction and demolition, a waste recycling rate of at least 70% will be achieved.

These quotas ensure the national successes of the cycle economy and provide impulses for further development. The quotas, which are partly above the EU targets, take into account both the existing recycling level in Germany and the economic feasibility.

2.2.3 §9 and 15 Promotion of Separation and Collection

Recycling is promoted by separation and separate collection of different waste streams. Besides the existing demands ([3], §15) now, in addition, for hazardous waste, the mixing ban is implemented in KrWG [3], §9.

However, some requirements are "not included", i.e. the KrWG [3] does not ban the mixing of waste with other waste with other properties (article 10(2)) when collecting. Furthermore, the KrWG [3] does not include the restriction of separate collection if this is environmentally practicable (article 11(1)) and therefore goes beyond the WFD, by not including this possibility for derogation. Further, the requirement that separate collection has to be appropriate to meet the necessary quality standards for the relevant recycling sectors is not included (article 11(1)). "Additionally", the KrWG [3] includes an obligatory requirement for the separate collection of biowaste (Art. 22, WFD 2008), including an exact deadline for implementation (1 January 2015).

2.2.4 Main Strategies Implementing Separate Collection

Germany is a federal republic consisting of 16 federal states, and the responsibility for waste management and environmental protection is shared between the national government, the federal states and local authorities.

The National Ministry of the Environment sets priorities; participates in the enactment of laws; oversees strategic planning, information and public relations; and defines requirements for waste facilities.

Each federal state adopts its own waste management act containing supplementary regulations to the national law, e.g. concerning regional waste management concepts and rules on requirements for disposal. There is no national waste management planning in Germany. Instead, each federal state develops a waste management plan for its area.

Paper, metal, plastic and glass waste, as well as biowaste, shall be collected separately at the latest from 1 January 2015.

The Packaging Ordinance [4] transposes the requirements of the EU directive on packaging and packaging waste into national law and provides requirements for separate collection and specific targets for recycling and recovery of packaging waste.

The stepwise implementation of the Packaging Ordinance had the following milestones [5]:

- At the latest by 31 December 2008, a minimum of 65% by weight of packaging waste must be recovered, and a minimum of 55% by weight of packaging waste must be recycled.
- For packaging from private households, the following recycling rates are demanded: plastics 36%, composite materials 60%, glass 75%, tinplate 70%, paper and cardboard 70%, aluminium 60%.

– Product responsibility for the waste management of packaging either as placing takeback opportunities in the markets, reusing or recycling the packaging or paying for a third party.
– Implementation of recycling bins for plastics and metals in order to increase recycling.
– Existing yellow bins (for packaging) can also be used for so-called non-packaging of similar material.
– Ongoing discussion about a new law for recyclable material.

The performance of the development of recycling performance in Germany (DE EEA 2013) can be summarised that recycling has increased from 48% of MSW generated in 2001 to 62% in 2010. The EU target of 50% recycling by 2020 has already been met; there was no increase in the recycling level of MSW between 2006 and 2010, whereas incineration has increased (DE EEA 2013).

3 Realisation of Legal Principles

3.1 Case Study: Waste Paper

In the last 20 years, the amount of separately collected waste paper increased significantly. Comparing the collection of the last 20 years, there is an increase of the use of waste paper as a secondary raw material and the decrease in the amount of waste paper in the residual waste.

In 2013, roughly 22.4 million Mg paper was produced mainly based on natural resources like wood, recovered fibres and minerals in Germany (VDP 2014). In Germany and worldwide, recovered paper is the most important raw material for the paper industry. Nowadays, resources, products and waste materials are reused or recycled. With a recovered paper utilisation rate of 74% (D 2013), the paper industry is on the way to a circular economy. The products are used again and again as secondary fibrous raw material after their first and second use phase. Table 2 shows the paper for recycling balances in Germany over the last 20 years [7].

Table 2 Comparison of paper balances in Germany in 1992 and 2011 [6]

Recovered paper	Unit	1992	2011	Change (%)
Paper/cardboard production	Mio. Mg	12.941	22.706	75
Recovered paper: end consumer	Mio. Mg	12.268	16.677	36
Nonrecyclable recovered paper: end consumer	Mio. Mg	0.687	1.880	174
Separately collected/recovered paper in household and commercial	Mio. Mg	6.785	13.846	104
Recovered paper in the waste management system	Mio. Mg	5.483	2.831	−48

Caused by a high amount of paper use in households as well as in small and medium enterprises, a high amount of waste paper occurs. Paper production increased from 1990 until 2011 from 12.8 Mio. t to 22.7 Mio. t. Waste paper utilisation increased from 49 to 71%. Due to the extended demand on waste paper, the separate collection of waste paper was continuously increased by different systems.

3.2 Case Study: Biowaste

Actually, in Germany an average of 100 kg biowaste/cap/a are collected separately.

Caused by the legal requirements of the Circular Economy Act [3], especially by 11/1, a further increase of the separate collected amount of biowaste is expected.

Regarding Kern et al. [8], more than 50% of people have no separate biowaste bin. In 72 of 388 municipalities, no biowaste bin is offered. In the municipalities that offer a biowaste bin, not all people have access to the separate collection of biowaste (Table 3).

There are different utilisation pathways of not separately collected biodegradable waste, such as home composting, collection as residual waste and illegal disposal in forests or in the countryside.

Approximately 10 kg of biowaste/cap/a will remain in the residual waste also by implementing a nationwide separate collection of biowaste. In addition, we will not mobilise the biowaste, as it is home composted. In some rural areas, separate collection is environmentally and economically not practicable.

4 Summary and Outlook

In Germany within the last several years, we considered a declining amount of residual waste by increasing the collection of organic and recyclable material.

Recycling is already well-established in the fields of paper and glass. Waste paper and waste glass are the most important raw materials for paper and glass production. But there are other potential valuables for recycling deducible, such as textiles and plastics, whereas the recycling rates need to be increased in order to reach the demands from the EU.

Table 3 Access to separate collection of biowaste [8]

Access to biowaste bin	Municipalities	Inhabitants	Municipalities (%)	Inhabitants (%)
Biowaste bin nationwide	281	62,834,634	72.4	76.9
Biowaste bin in subsections	35	8,323,282	9.0	10.2
No biowaste bin	72	10,525,917	18.6	12.9

References

1. DESTATIS (2016) Statistisches Bundesamt: Umwelt – Abfallbilanz (Abfallaufkommen/-verbleib, Abfallkennzahlen, Abfallaufkommen nach Wirtschaftszweigen) 2014. Statistisches Bundesamt, Wiesbaden
2. Directive 2008/98/EC on waste (Waste Framework Directive). http://ec.europa.eu/environment/waste/framework/
3. KrWG (2012) Kreislaufwirtschaftsgesetz. http://www.gesetze-im-internet.de/krwg/index.html
4. VerpackV (1998) https://www.gesetze-im-internet.de/verpackv_1998/BJNR237900998.html
5. Europaen Commission (2015) Assessment of separate collection schemes in the 28 capitals of the EU. Reference: 070201/ENV/2014/691401/SFRA/A2. Final report
6. Bilitewski B, Kügler T, by order of VDP (2014) The paper value chain. Development and perspectives. In: Presentation on the PTS-conference for cooperation, 7 Mar 2014 (in German)
7. Dornack C, Seidemann C, Kappen J, Wagner J (2015) Future composition of recovered paper in Europe – expectations causes and effects. In: Thomé-Kozmiensky K, Goldmann D (eds) Recycling und Rohstoffe, vol 8. TK Verlag, Berlin, pp 501–515. ISBN: 978-3-944310-20-6 (in German)
8. Kern M, Raussen T, Funda K, Lootsma A, Hofmann H (2009) Aufwand und Nutzen einer optimierten Bioabfallverwertung hinsichtlich Energieeffizienz, Klima- und Ressourcenschutz. UBA. http://www.uba.de/uba-info-medien/4010.html

Separate Collection of Waste Fractions: Economic Opportunities and Problems

Henning Friege

Abstract Separate collection of valuables from waste is of growing importance for the conservation of resources and the mitigation of greenhouse gas emissions from landfills. Moreover, the separation of certain waste fractions, such as food waste, is necessary to ensure that landfills and – more importantly – incinerators are managed properly. It is therefore necessary to examine the reasons and motivations for separating waste. Separation and recycling of waste fractions should decrease the overall cost of waste disposal for citizens and public bodies. This can only happen if the authorities take into consideration some important "stumbling blocks," i.e. physical and socioeconomic indicators and prerequisites, when introducing a recycling system. Four examples (landfill tax as an incentive for separate collection, recycling of used paper and cardboard, collection of bio-waste, recycling of mixed packaging waste) have been investigated in order to evaluate the reasons for successful and unsuccessful attempts at resource recovery. Economic incentives for waste segregation are very important and should be tested in pilot studies or through simulation games, because major differences between opportunity costs and costs for alternative treatment options may lead to unwanted behavior by waste producers and/or citizens. Furthermore, citizens' behavior regarding the separation of valuables, their cultural background with respect to waste management, and social norms must be taken into account when planning collection schemes. Obviously, convenient access to collection systems is essential. Citizens must become accustomed to these systems; long-term awareness raising helps to optimize the successful collection of recyclables.

Keywords Economic incentives, Extended producer responsibility, Informal collection, Separate collection, Stumbling blocks for recycling

---

H. Friege (✉)
N3 Thinking Ahead Dr. Friege & Partners, Scholtenbusch 11, 46562 Voerde, Germany
e-mail: Friege@N-hoch-drei.de

R. Maletz et al. (eds.), *Source Separation and Recycling*,
Hdb Env Chem (2018) 63: 11–30, DOI 10.1007/698_2017_24,
© Springer International Publishing AG 2017, Published online: 20 September 2017

Contents

1 Scope and Introduction

Waste management is part of the public duty to prevent hygienic and environmental risks. Incorrect and inadequate waste management often leads to health problems and damage to the environment [1]. That is why national, regional, or local governments are in charge of organizing the collection and disposal of waste. These activities are financed from taxes and/or charges paid by waste producers. In many developing countries, funding for waste management is insufficient, which might result in a far higher burden on the national economy, as can be seen in the case of large dumpsites [2]:

– Emission-related diseases suffered by people living near large-scale dumpsites
– Contamination of groundwater by leachates and/or rivers by effluents from landfills

If public expenditure for waste collection and disposal could be decreased by revenues from resources recovered from waste, the financial burden for the public bodies concerned could be mitigated.

Early recycling programs caused, in some cases, higher overall expenditure than disposal. At present, waste management systems in many countries include separate collection of recyclable materials. The advantages to be gained from carefully considered recycling programs are widely accepted in scientific literature as well (see, for example, [3–6]), but they depend on a number of prerequisites and a reliable framework for the relevant stakeholders (see, for example, [7]). Waste management should be regarded as a multidimensional scientific framework which incorporates technical, social, economic, environmental, and other aspects. Especially in the case of recycling, several aspects are interlinked and interdependent. Though technical solutions and equipment can be transferred from one country to another, the answers to challenges for resource recovery may differ considerably depending on the level of development as well as varying social and economic conditions.

1.1 Guiding Questions

In the following section, three questions are investigated:

– Separate collection of waste fractions – when does it pay off?
– Can public waste management save financial resources through separate collection?
– How can separate collection be supported by economic incentives?

These questions will be discussed against the backdrop of experience and examples from Europe, especially from Germany, where the separate collection of waste fractions by public bodies and private companies has developed over about 40 years. These developments were fostered by national regulations (Germany, Austria, The Netherlands, Switzerland, Denmark, etc., see, for example, Dornack [8]) which prohibited the disposal of degradable waste on landfills and set recycling targets for specific waste streams at the European level, e.g. WEEE [9] among others. The introduction of what is referred to as the "waste hierarchy" by European law [10] encouraged the Member States and the municipal authorities to look for further possibilities for material recovery.

1.2 Basic Conditions for the Recovery of Valuables from Waste

Collection and recycling are subject to a number of physicochemical and socio-economic conditions which can be generalized in the form of seven "stumbling blocks" [11, 12], which represent the most significant types of obstacles. In the following section, only those stumbling blocks are described which are relevant for answering the questions listed above:

– *Entropy (ΔS)*: All recycling processes are confronted with the entropy dilemma. Following statistical thermodynamics, entropy can be used as a yardstick for the disorder of a closed system [13]. To achieve greater order in the system, external energy has to be fed into the system. It is therefore impossible to close recycling loops completely as was already published by Stumm and Davis in 1974, cf. [14]. It is very difficult to recover valuable materials encased in products, and energy is needed for their separation. According to a model based on information theory [15], the profitability of a recycling operation can be derived from just a few economic and physical figures, including the absolute measure of material mixture within a used product.
– *Dissipative use (D!)*: Consumption of goods means a dissipative dispersion of products. Waste management companies collect dissipated goods after use. The

higher the dissipation rate, the less devices can be collected separately in relation to the number of devices sold.[1]

– *Dual character of waste and resource ($H \leftrightarrow R$)*: Waste is Janus-faced: it is either a resource or a peril. The more the material or product in question is mixed up with potentially hazardous substances, the more difficult the recovery of valuables is. This is also limited due to the danger of transferring critical substances into new products made from secondary materials [17–19].
– *Socioeconomic situation (ΔE)*: From an economic point of view, waste is a good with a negative price, i.e. for waste disposal, a price has to be paid depending on the quality and the amount of waste. If waste contains valuable components, the waste owner might decide to keep this waste fraction separate in order to decrease the price to be paid for the residual waste. He might also decide to collect valuable parts of the waste from other waste owners and seek to generate additional income. For this decision, the individual socioeconomic situation is of utmost importance. High income disparities are an enormous incentive for informal collection activities triggered by the market price of the waste fraction in question, as can be seen in the relationship between formal and informal collection in large cities (see, for example, Rodic et al. [20], and the analysis of the Beijing informal waste management published by Steuer et al. [21]).
– *Role of time (Δt)*: Time is a crucial challenge for waste management for several reasons: Firstly, consumption habits change with time and thus lead to unforeseen changes in the volume and/or the composition of waste. Secondly, valuable resources cannot be substituted with secondary raw materials as long as they are in use. This sounds very simple, but the consequences can be dramatic in the case of societies threatened by the absence of already scarce resources in the near future. Thirdly, chemicals banned for use in new products are present in the waste and thus disrupt recycling processes (see above: $H \leftrightarrow R$).

2 Economic Basis of Separate Collection

2.1 Economic Efficiency of Collection and Recycling

With regard to the economic efficiency of the collection and recycling of separated waste fractions, it is necessary to differentiate between two perspectives:

[1]The dissipation dilemma can be demonstrated using platinum (Pt) as an example: Pt is used in the chemical industry (catalysts, laboratory equipment) and for the production of glass (fiber glass nozzles). The recycling rates are >80% and >95%, respectively. As to Pt from automobile catalysts, the recycling rate is <<50% [16], though the loss of Pt from car catalysts during the use phase has been minimized. The recovery of Pt from smaller devices used by consumers is far less.

- The perspective of the waste management administration responsible (e.g., city, region)
- The perspective of the waste producer, waste owner, or waste trader

As indicated in Table 1, there are several potential motivations for administrative bodies to collect waste fractions separately.

If separate collection is driven by strategic or ecological reasons, even higher expenses might be accepted by administrative bodies in order to reach the goals in question (e.g., rapidly declining landfill capacity). This mostly also leads to lower costs in the long term.

The waste producer's perspective is primarily determined by the opportunity costs for waste disposal [22], as indicated in Fig. 1. The difference between the disposal costs and the costs (or even revenues) for separation and recycling is an economic incentive for the waste producer to separate certain fractions for recycling, like waste owner and waste trader as well. Economic advantages or disadvantages are an important factor which influences the behavior of waste producers. As has been proven empirically, there is a close relationship between the percentage of recycling investments (as compared to the total budget) and the price for waste disposal: Japanese and German companies invest more money in recycling activities when the price level for waste disposal increases [23]. However, regulations, convenience as well as cultural and ethical attitudes are also important (see, for example, [24–26]).

From the perspective of the administrative body responsible or from that of a company commissioned with waste collection, several prerequisites have to be fulfilled in order for a collection scheme to be successful. First of all, the financial background of investments in waste treatment facilities differs from other sectors.

Table 1 Potential motivations for separate waste collection from the standpoint of a public body responsible for waste management

	Potential motivations for separate collection	Economic consequences
Strategy	Extending the operational life of a landfill Incineration capacity insufficient	Saves money in the long run, not driven by short-term revenues
Ecology	Safe depositing of hazardous waste Decreasing GHG emissions Saving resources	Minimizes costs; action not driven by revenues
Social issues	Help for unemployed or poor inhabitants	Saving costs for unemployment; action not driven by short-term revenues
Economy	Revenues for the municipal budget Policy pressure to decrease waste charges	Short-term and long-term revenues from recycling necessary

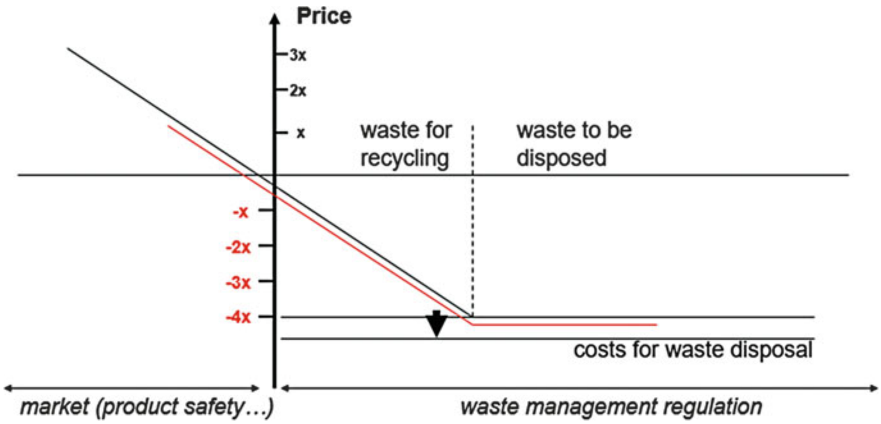

Fig. 1 Opportunity costs for waste disposal (*black line*) and the decision pathway of the waste owner (*red line*). They describe the growing incentive in the case of higher costs for waste disposal (*black arrow*) or decreasing costs down to small revenues for separated waste (simplified presentation following [22])

Waste management assets are characterized by their irreversibility and by their subadditivity [27]:

- An "irreversible" asset cannot be transferred to other markets when the investment turns out to be unprofitable. This holds true for nearly all investments in waste management with some exceptions, e.g. trucks designed for container transport.
- The specific costs for waste treatment in landfills, incinerators or advanced sorting facilities strongly depend on capital expenditures rather than on operating expenses. Capital costs as well as overall costs are therefore "subadditive": Larger installations have lower specific costs (money invested vs. capacity) than smaller ones, e.g. boilers and grates for incineration, volume needed for landfilling. This is not the case for waste logistics.

These specific features of assets in the waste sector lead to severe losses ("stranded investments"), if return on investment is not flanked by long-term agreements on the volume of waste to be treated and on prices. A number of assets are presented in Fig. 2 with respect to irreversibility and subadditivity ([27] and literature cited therein). Due to the high subadditivity and irreversibility of investments in landfills, WtE plants, and advanced sorting plants, investments of this type are undertaken by either public bodies or companies which reign over a monopolistic market.

There is not only a need to finance suitable logistics systems for collection, but also to invest in sorting and disposal facilities in order to arrive at a complete and sustainable waste management system. Expenditures for collection and disposal on the one hand and revenues from recycling on the other hand are connected with

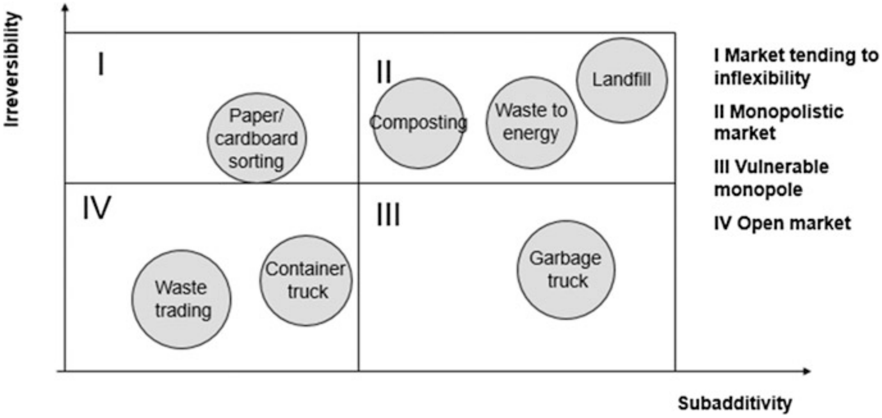

Fig. 2 Specific features of assets for waste management and their influence on market conditions (adapted from Cantner [27])

respect to budget. Economic efficiency means sufficient liquid funds for the current fiscal period and timely return on investment. Depreciation takes about 20 years for sorting plants or WtE facilities, and for landfills even longer. This minimizes capital expenditures and ensures continuous but acceptable overall costs funded either by taxes or by charges paid by citizens. Obviously, economic efficiency also depends on the revenues from energy or material gained from waste. Thus the revenues from separately collected fractions depend on

- capital and operational costs for collection,
- amount and quality of the input material,
- price to be paid for the waste,
- capital and operational costs of the facilities, and
- market prices for the recovered material.

The easiest way to achieve profitability is a continuous delivery of waste at a fixed price, but this is a rare case. Volume and quality of the input material links financial considerations to the waste collection system. If the quality of the collected material is poor, operational costs for sorting will increase as well as costs for the disposal of residues from sorting. If the quality of the input material is rather low, sorting will ultimately not pay even if considerable effort is made. In such cases, the additional costs for separate collection, capital expenditures for the sorting facility, etc. are a burden on the budget. For economic efficiency, correct separation of valuables by citizens is essential in order to achieve surplus revenues from recycling. The effort necessary to reach this goal is often underestimated [28].

2.2 *Design of Waste Management Systems for Successful Collection*

"Success in separate collection" means reaching the specific goals of the region or city as presented in Table 1. It is therefore worthwhile examining some examples.

Strategic Motivation In many developing countries, household waste exhibits very low calorific value due to a high concentration of organic fractions, "which are significantly higher in middle- and low-income countries (averaging 46–53%) than in high-income countries (averaging 34%)" ([1], p. 56, see also [20]). The water content originates from a high percentage of fruit and vegetables in daily nutrition and also from steamed rice and vegetables. Physical and chemical properties of this waste hamper not only incineration but also landfilling. In the case of incineration, additional energy is needed to dry the waste on the grate before it is burned. This means less energy recovery or even a negative energy balance. In cases like this, "waste to energy" becomes meaningless; anticipated revenues from energy are lost. As for landfills, the high percentage of water

- impedes the construction of higher waste piles,
- leads to the solution and transport of contaminants which endanger groundwater and rivers nearby, and
- accelerates degradation processes and therefore the emission of methane.

In the latter case, more space for landfilling is required compared to waste with low moisture content. Additional costs may also be incurred through the purification of raw water to ensure a safe drinking water supply in the area surrounding the landfill. To reduce the moisture content in residual waste significantly, separate collection of food waste from households as well as organic waste from markets and the food industry seems to be the easiest solution. The yardstick for the economic efficiency of this separate collection is defined by saved expenditures for additional fuel and operational costs due to lower throughput (incinerator) or treatment of high leachate volume, purification of raw water, or additional land use (landfill), respectively.

Ecological Motivation Residual waste often contains hazardous waste from craftsmen's workshops or small-scale industry, sometimes also from hospitals. This waste

- is a hazard to garbage collectors,
- may lead to accidents at the landfill or in the incinerator bunker (self-ignition, explosion), and
- contaminates leachate from the landfill.

On the other hand, these types of waste sometimes include valuables such as sludge from plating or residues from the plastics industry. Recovery of valuables from commercial waste therefore already helps to recuperate collection costs.

Additional costs for the continuous cleaning either of leachates or – far worse – of drinking water can be saved.

Social Motivation Many underprivileged people, especially in developing countries, work as garbage collectors. They concentrate on those items and waste fractions which can be re-used or recycled and promise a small profit when sold. The working conditions of informal collectors and recyclers are normally poor and cause health problems, as well as prevent children from attending school (for an overview, see Wilson et al. [29]). From an economic point of view, the consequences of these poor working conditions cost public money in the long run. Moreover, the activities of the informal sector can sometimes severely disrupt waste management activities undertaken by public authorities. "The challenge for authorities is to support and promote the entrepreneurship, flexibility and productivity that characterize the informal sector, while striving to reduce the sector's negative aspects. . . Such an approach would imply giving a mandate to the informal service providers, integrating them to work alongside the formal sector and thus incorporating them in the system." ([1], p. 178). Saved costs for social welfare and optimized collection and recycling of valuables on the one hand and the expense of integrating the informal sector alongside the companies responsible for waste management on the other (for further considerations see Cavé [30] and Velis et al. [31]) can also lead to a profitable result from a holistic perspective.

Economic Motivation In this case, either the tax income required for waste management or charges paid by households are decreased. In both instances, the background is usually a policy decision (e.g., by the city council) driven by budget needs or prompted by dissatisfaction amongst the electorate. This goal can be achieved by collecting potentially valuable waste fractions which are separated at the source and sale of these separated materials. The goal is met if revenues from the separated waste fractions continuously exceed the costs for a second collection system (e.g. trucks, waste bins, etc.), for sorting waste from the separated fractions, and the disposal of materials which cannot be recovered properly.

In all the cases described above, citizens' co-operation in separating their waste into fractions is a crucial prerequisite for a successful collection scheme. Apart from people's (possibly changing) attitudes towards the task of waste separation, informal activities can endanger new collection systems for valuable fractions. It might therefore make sense to combine the economic and the social motivation (Table 1) for recycling in order to integrate the informal sector into the public system [32], thus providing economic benefits for both. "Increasing segregation at the source is a critical component of any programme to include the informal sector into mainstream waste management and would both improve their working conditions and improve their livelihoods by improving the quality of the recycled materials." ([1], p. 80). If a high percentage of the collected material is exported, revenues from recycled waste depend on global market conditions. If collection is only possible at the regional level, then prices are determined by regional forces. Most secondary resources are subject to price volatility on international markets, and this is especially the case with some non-ferrous metals. "Secondary materials have traditionally been used to ‘top up’ a relatively stable supply of primary materials… in response to short-term variations in market demand, so their prices have tended to be even more volatile than those of the related primary commodities.” ([1], p. 80). Market development since about 2005 indicates increasing price volatility for most raw materials, both primary and secondary.

3 Experience Gained with Economic Incentives for the Separation of Waste Fractions

Economic incentives for waste prevention and/or waste recycling can be based on

- deposits for products,
- charges for waste volume.

Deposits have been widely introduced in European countries (Germany, Switzerland, Norway, Sweden, Estonia, Finland, Croatia, etc), in the United States (which are known as “bottle bills” found in about 50% of all states), and in Japan for the packaging of consumer goods and some other short-lived products. In Germany, deposit legislation was greatly extended in 2006 for beverages sold in returnable bottles in order to avoid the breakdown of the market. The deposit for one-way bottles and cans for beverages is about double that of returnable items and is an incentive to

- buy beverages in returnable bottles,
- prompt the consumer to bring one-way bottles back to the retailer.

In 2012, the return ratio of one-way bottles and cans was 95.9% [33]. In the area of commercial goods, deposits are used to guarantee the return of transport pallets, safety containers for chemicals, etc. These systems are restricted to items with a short lifetime or – in the case of commercial contracts – to items which are frequently exchanged with different customers. Deposits normally do not work very well with products for long-term use.[2]

In many European countries, private households and commercial companies pay charges for waste services provided by local or regional authorities. These charges recover the expenses incurred by the bodies responsible. In the following section, the considerations and results of some economic incentives are described in order to gain an impression of the successful or sometimes “risky” design of systems for segregated collection.

[2]The economic restraints for deposits in the case of products with a long usage period cannot be described here in detail. It should be noted that the value of a complex product after operational life cannot be estimated reliably. Moreover, high deposits for products which are in use for a long time extract considerable liquidity from the capital markets.

1. *Landfill tax*: Taxes for landfilling waste have been introduced in a number of countries (e.g., Belgium, The Netherlands, United Kingdom, Switzerland, some US states – see, for example, [34]) with the aim of accelerating the construction of sorting and incineration plants. This tax is not paid directly by the consumer but by the municipal and commercial waste owners. In general, the level of the landfill tax is increased yearly, thus doubling or trebling the price for disposal. In Belgium, the landfill tax resulted in a switch to material and energy recovery from waste within about 10 years. In Great Britain, changes in the waste collection system are now underway, triggered by the landfill tax which has been raised to 80 GBP and therefore now exceeds landfill prices by about 100–200%. When the additional costs are transferred to the citizens, political pressure for alternative waste management options, i.e. recycling and incineration, increases. In this way, waste owners are incentivized to keep valuable fractions separate in order to save money, because waste charges increase as a result of the landfill tax.
2. *Saving costs for residual waste disposal by collecting used paper*: In most European countries, used paper and cardboard are separated from residual waste. In Germany, the current recycling rate is about 74% (specific amount 186 kg inh^{-1} year^{-1}) in comparison to the volume of material put on the market [35]. Higher collection rates can hardly be achieved due to the proportion of paper from sanitary use. At least in Germany, the quality of the collected paper is very good and yields 75% (±6%) graphic paper and 23% (±6%) packaging paper and cardboard with an average proportion of 2% (±1%) residual waste [36]. The incentive for citizens to collect used paper and cardboard stems from:

   (a) Regulation: Waste owners are obliged to keep paper and other materials separate from residual waste and deliver it to the municipality responsible.
   (b) Convenience: “Blue bin” or other curbside collection is available for ~80% of all households; deposit containers are available in densely populated areas.
   (c) Economy: Less residual waste to be disposed d saves money, even if a small amount of money has to be paid for the collection of the “blue bin.”

   As the share of waste paper and cardboard in household waste increases from 6% in low-income countries to 24% in high-income countries [37], there is a good opportunity, especially for middle- and high-income countries, to decrease the waste charges imposed on citizens. On the other hand, cities can generate revenues from sales of used paper. For an average German municipality (own calculation), this pays off as follows:

   - Costs for separate collection of used paper/cardboard ~45 €/t
   - Costs for sorting and bundling of sorted material ~20 €/t
   - Revenues from sale of sorted material ~100 €/t

   With respect to the 186 kg (volume collected, see above), net earnings are about €6.50/inhabitant, which represents between 5 and 15% of the normal expenditure for waste disposal. It should be noted that the separate collection of waste fractions such as used paper and cardboard, used glass or textiles takes place continuously, even if market prices for secondary materials are low, so that people become accustomed to separating waste on a daily basis.

Obviously, commercial and informal waste collectors are motivated to interfere in municipal waste collection if prices are high. As such activities impede the continuous collection of paper and cardboard by the cities, the German Waste Law was amended to regulate competition between commercial and public waste management [38]: Commercial companies and charities are now obliged to register any intended collection campaigns. The authority responsible may prohibit such collection for several reasons, e.g. if the budget covered by waste service charges is affected to a certain extent. As can be seen from studying a 2-year period after the amendment, 3% of all prior registrations by private companies for separate paper collection were rejected [39].

3. *Saving costs for residual waste disposal by collecting biowaste*: European law obliges Member States to collect biowaste (waste from kitchens and gardens) separately in order to keep this degradable material away from landfills [10]. In Germany, the volume of separately collected biowaste is in the range of about 100 kg inh^{-1} $year^{-1}$ ([40] and literature cited therein).

   The incentive for citizens to collect biowaste separately stems from:

   (a) Regulation: Waste owners are obliged to keep food and garden waste separate from residual waste.
   (b) Convenience: "Brown bin" door-to-door collection is offered in nearly all cities.
   (c) Economy: Less residual waste to be deposited saves money, even if a small amount of money has to be paid for the collection of the "brown bin."

   Biowaste is usually treated aerobically to produce compost. Anaerobic treatment yielding biogas and organic fertilizer is increasingly important. Apart from alleviating the problems caused by organic waste on landfills, separate treatment of biowaste also increases the calorific value of residual waste for incineration thus yielding higher revenues from energy sales. Contamination of biowaste with residual waste, plastics, etc. hampers both treatment options. Farmers will not accept compost or fertilizer containing plastics. The degree of contamination varies from 0.9 to 12% w/w. High contamination very often corresponds to high population density ([41] and literature cited therein).

4. *Extended producer responsibility (EPR) systems for packaging*: In the case of EPR, the producer assumes responsibility for his product again after its usage period. When the product goes into the waste bin, the physical and/or economic ownership for the waste shifts from the consumer to the producer. The idea behind this instrument is "the provision of incentives to producers to take into account environmental considerations when designing their products" [42]. For packaging waste, individual take-back systems would be far too expensive. Collective solutions are therefore provided by producer responsibility organizations (PRO), which bundle the take-back obligations of various producers of packaging material and collect this waste fraction. In most cases, the result of

EPR was the financing and creation of infrastructure for post-consumer recycling. However, there is no concurring opinion on the cost-effectiveness of this strategy [43]. The economic consequences are twofold: The producer pays for collection and recycling and in this way comes under pressure to design and create products suitable for recycling. This is, however, only of minor importance in the case of collective product responsibility systems, "which may distort competition and allow free-riding on design for recycling efforts to reduce product recovery costs" [44]. The municipality saves part of its budget money for some of the waste generated by citizens.

Implementation of the EC packaging directive differs considerably in the individual Member States (see Cahill and Grimes [45] for an overview).

In Germany, collective systems ("Duale Systeme") sell licenses for packaging material to the producers who undertake to collect and recycle an equivalent amount of packaging waste. The collective systems then finance the collection, sorting, and cleaning of recovered material. The operational work is carried out by tendered contractors, i.e. private or public companies. The incentive for citizens to separate packaging materials stems from:

(a) Regulation: Waste owners are obliged to keep these materials separate from residual waste and to deliver it to the producer responsibility systems.
(b) Convenience: Curbside collection ("yellow bin," "yellow bag") for all lightweight packaging (plastics, cans, etc.) is common. For used glass and paper, containers are available in the streets (besides the blue bins for used paper and cardboard already mentioned above).
(c) Economy: Citizens save money with the disposal of residual waste.

As packaging waste (lightweight packaging material, glass, and cardboard used for packaging) represents about 20% (w/w) of household waste [46], municipalities save an equivalent amount of money with the disposal of residual waste. Used glass and cardboard from packaging are often collected in containers which induce relatively low costs. There is door-to-door collection for lightweight packaging waste (plastics, cans, composite materials, etc.). The average full cost (sum of expenditures and revenues) for the management of packaging waste is €553 Mg^{-1} with respect to the volume of licensed materials and €281 Mg^{-1} for the separately collected waste [47]. This means far higher costs compared to residual waste. The high costs for the management of lightweight packaging waste are due to

- complicated sorting aimed at separating different packaging materials, i.e. polyethylene, polypropylene, polystyrene, PET, aluminum, tinplate, cardboard/plastic compounds,
- poor quality of the material collected, which includes 35% (on average) of other waste fractions [48].

4 Discussion

From a cost-accounting perspective, setting the charges due for a specific waste fraction should reflect the percentage of the costs incurred by the municipality or the producer (in the case of EPR systems) for this fraction. However, this is only part of the solution because the following question still needs to be answered: Which economic incentive prompts the waste owner to bring back used items or sort his waste correctly? As presented in Fig. 1, waste charges should be in relation to the waste owner's opportunity costs for disposal. This also means that an individual fee for waste disposal is crucial for further incentives which support separate collection of waste fractions.

With respect to the disposal of short-lived products, it is clear that the economic incentive must be high enough to prompt the waste owner to bring back used items to a retailer or a take-back machine despite the additional effort. The economic incentive must therefore be selected not only under consideration of the specific costs for a waste fraction, but also of the desired behavior. This may lead to incentives which do not mirror the costs for the waste fraction in question, but optimize the collection result with respect to quality and quantity. In the case of packaging, the deposit value is mostly higher than the market value of a plastic bottle or a tin can. On the other hand, such a high economic incentive may lead to unwanted effects, e.g. shipment of empty bottles from regions without a deposit into areas where deposit charges are implemented. Deposit regulations should therefore be harmonized between adjacent regions or countries to avoid windfall profits in the case of no (or low) deposits in one region and high deposits in other regions, as has been observed between Germany and the Netherlands.

The positive experience gathered with landfill taxes (example No. 1) shows that economic incentives work especially well in cases where a limited number of stakeholders are involved, invoicing schemes are simple, and there is the possibility of transferring the costs to the waste producers. The cities and regions involved are in a position to enforce material and energy recycling. In so doing, they reduce their own costs by decreasing the amount of residual waste. Landfill taxes proved to be a major incentive [34] to invest in waste-to-energy and recycling plants. In view of large differences in landfill prices in adjacent countries, the cross-border transport of waste must be strictly controlled (e.g., compulsory notification within the EU).

Example No. 2 shows successful sorting efforts by citizens which lead to high quality of the separately collected fractions. This is not only due to the economic incentive but also thanks to convenient collection systems and long-term awareness raising amongst waste producers. Although prices on the paper market are volatile, there is reasonable surplus income for municipalities over time. Increasing revenues may lead to a situation where collection also pays off for private companies, even if they have to invest in new bins and trucks. As outlined above, these assets have relatively short depreciation periods compared to sorting facilities. To avoid disruption between private and municipal collection, regulations in European countries in general distinguish clearly between household waste and other parts of the waste market.

It can be concluded from example No. 3 that a similar system to example No. 2 leads to worse results with respect to quality. In a detailed questionnaire distributed among the citizens of a small town [49], the following reasons for contamination were identified:

- Use of plastic bags for collection at home which are deposited in the "brown bin"
- Misconception about "degradable" plastic bags
- Incorrect sorting of sanitary organic waste, e.g. diapers
- Saving money for residual waste disposal

Some of these misconceptions and types of behavior can be remedied through information campaigns. To fight intentional misuse stimulated by price advantages (unwanted effect caused by a high economic incentive), many municipalities monitor biowaste bins in areas where high contamination is observed with the aim of penalizing the owners.

Example No. 4 displays unsatisfactory results. The differences between the second and the fourth example can be linked to two of the stumbling blocks described in Chap. 1.2: Used paper and cardboard are a uniform waste fraction which can easily be identified by citizens; sorting is only necessary to eliminate a few contaminants and adds value through the output of various grades of paper. Used packaging comprises a high number of different materials, of which only some are intended for collection in the "yellow bin." Others are excluded, e.g. glass, cardboard, and wood. The entropy factor (**ΔS**) is considerably higher for the yellow bin compared to the cases mentioned before. In contrast to the previous examples, where the charges for waste management are determined by the municipality, the costs for waste management of packaging are integrated in the price of the product. This changes the perspective of the citizen who is confronted with charges for his residual waste, whereas the disposal of packaging waste is free of charge. This difference is a powerful economic incentive for the waste owner (**ΔE**) and can lead to misuse of the collection system for the disposal of other waste fractions, especially residual waste. This behavior is rarely penalized due to the different responsibilities of municipalities and PROs: Local governments save money if citizens dispose of part of their residual waste in a system financed by a PRO. On the other hand, the PROs are reimbursed by a great number of producers, who include these costs when calculating the price of their products.

5 Conclusions

The economic efficiency of waste management can be significantly enhanced by the bodies responsible if separate collection is properly planned and also takes into account strategic, social, and ecological goals. Prior to planning, motivation, which is strongly dependent on the intended waste management system, must be clear.

Changes in waste streams may occur over time, such as the current increase in used cardboard and the corresponding decrease of used paper due to changing consumer behavior. Although waste management facilities have to be planned for a long operational lifetime, partial refurbishment might be necessary and should be integrated into the budget. Extrapolation of future waste streams from today's waste should be complemented by an assessment of future output based on current streams of products put onto the market (input). In order to plan long-term investments, a sensitivity analysis of the relevant economic parameters is strongly recommended.

Economic incentives for the separation of waste fractions or for waste prevention are very helpful and should be regarded as measures to accompany suitable regulations as has been concluded by Zhang et al. [50] with respect to the situation in China. Waste management systems can be severely disrupted by unforeseen conflicting economic interests. This is especially important for all activities involving high investments with long depreciation periods. In the case of waste fractions which yield low earnings due to the difference between expenditures for collection and revenues from material sales, commitment on the part of municipalities can be very successful. Earnings might be optimized by simple rules and long-term awareness-raising as well as convenient collection systems. This is also true for fractions which could be separated simply to avoid expenditure for residual waste treatment, such as biowaste.

When planning a collection scheme, citizens' attitudes towards the separation of valuables, their cultural background with respect to waste management (i.e., hygiene standards), social norms [24], and convenient access to waste bins or deposit container systems near their homes [26] must be taken into account. If economic incentives have already been introduced or will be in future, their impact should be tested in pilot studies or by simulation games. Major differences between opportunity costs and costs for alternative treatment options may lead to unwanted behavior, i.e. the contamination of separately collected waste fractions by individuals, as well as the disruption of municipal waste collection by private companies or scavengers. To overcome such problems, a bundle of regulatory as well as participative instruments can be introduced. Good governance is key to successful implementation of these instruments. Public acceptance for recycling systems can be obtained by intensive public involvement in the planning phase [51]. It is difficult to identify and integrate all relevant stakeholders, which means that risks still remain even after such a process. A general dilemma for citizens' participation stems from common misconceptions about recycling, e.g. naïve assumptions about the economic and ecological value of "closing loops" [28]. This may lead to misguided political decisions on the one hand and disappointment amongst citizens on the other, when people become aware of the long time period required to implement the system and of only slowly increasing revenues.

Prior to the installation of a recycling system, the stumbling blocks presented in Chap. 1.2 can serve as a simple tool to assess opportunities and risks: The greater the influence of one or more stumbling blocks for a specific waste fraction, the more problems have to be anticipated in further planning [11, 12].

References

1. UNEP/ISWA (2015) Global waste management outlook. UNEP, Geneva. ISBN:978-92-807-3479-9. http://www.unep.org/ietc/Portals/136/Publications/Waste%20Management/GWMO%20report/GWMO_report.pdf. Accessed 14 May 2016
2. ISWA (2016) A roadmap for closing waste dumpsites. In: International Solid Waste Association (ed) The world's most polluted places. Vienna. www.iswa.org
3. Callan SJ, Thomas JM (2001) Economies of scale and scope: a cost analysis of municipal solid waste services. Land Econ 77(4):548–560
4. Lakhan C (2015) Evaluating the effects of unit based waste disposal schemes on the collection of household recyclables in Ontario, Canada. Resour Conserv Recycl 95:38–45
5. Lavee D (2007) Is municipal solid waste recycling economically efficient? Environ Manag 40 (6):926–943
6. Tonjes DJ, Mallikarjun S (2013) Cost effectiveness of recycling: a systems model. Waste Manag 33:2548–2556
7. Mueller W (2013) The effectiveness of recycling policy options: waste diversion or just diversions? Waste Manag 33:508–518
8. Dornack C (2017) Waste policy for source separation in Germany. Handb Environ Chem. https://doi.org/10.1007/698_2017_114
9. EC (2012) Directive 2012/19/EU of the European Parliament and of the council of 4 July 2012 on waste electrical and electronic equipment (WEEE), OJ L 197/38-71
10. EC (2008) Directive 2008/98/EC of the European Parliament and of the council of 19 November 2008 on waste and repealing certain directives, OJ L 312/3-30
11. Friege H (2012) Resource recovery from used electric and electronic equipment: alternative options for resource conservation. Waste Manag Res 30(9S):3–16
12. Friege H (2012) Ressourcenschonung am Beispiel von Elektro- und Elektronikaltgeräten. II. Ansätze für einen effizienten Umgang mit nicht erneuerbaren Ressourcen (Resource conservation using the example of electrical and electronic equipment. II. Approaches for the efficient management of non-renewable resources). Müll Abfall 44(6):307–317
13. Brunner PH, Rechberger H (2004) Practical handbook of material flow analysis. CRC Press LLC, Boca Raton. ISBN:1-5667-0604-1
14. Schenkel W, Reiche J (2004) Abfallwirtschaft als Teil der Stoffflusswirtschaft (Waste management as part of the material flow management). In: Bilitewski B, Schnurer H, Zeschmar-Lahl B (eds) Müllhandbuch. Kz. 1417, Lfg. 2/04. Erich Schmidt, Berlin
15. Dahmus JB, Gutowski TG (2007) What gets recycled: an information theory based model for product recycling. Environ Sci Technol 41:7543–7550
16. Bringezu S, Bleischwitz R (2009) Sustainable resource management. Greenleaf Publishing, Sheffield. ISBN-13:9781906093266
17. Bilitewski B (2010) Sicherheitsbetrachtung aus einer globalen Perspektive für Konsumgüter hergestellt aus Recyclingrohstoffen (Security considerations from a global perspective for consumer goods made from recycled raw materials). Müll Abfall 42(12):582–585
18. Bilitewski B, Darbra RM, Barcelo D (eds) (2012) Global risk-based management of chemical additives, 1. Springer, Heidelberg. ISBN:978-3-642-24876-4
19. Bilitewski B, Darbra RM, Barcelo D (eds) (2013) Global risk-based management of chemical additives, vol 2. Springer, Heidelberg. ISBN:978-3-642-34572-2
20. Rodic L, Scheinberg A, Wilson DC (2010) Comparing solid waste management in the world's cities. ISWA Knowledge Base. www.iswa.org. Accessed 12 Dec 2016
21. Steuer B, Ramusch R, Part F, Salhofer S (2017) Analysis of the value chain and network structure of informal waste collection in Beijing, China. Resour Conserv Recycl 117:137–150
22. Baum HG (2013) Entwicklung der Abfallentsorgung im Lichter der widerstreitenden Steuerungskonzepte (Development of waste disposal in the light of the conflicting control concepts). In: Bilitewski B, Schnurer H, Zeschmar-Lahl B (eds) Müllhandbuch, Kz. 0138, Lfg. 2/13. Erich Schmidt, Berlin

23. Baum HG (2015) Economic conditions for recycling of waste – especially packaging waste. In: ISWA Beacon conference 2015, Hamburg. http://iswabeacon.obladen.de/images/presentations/Baum.pdf. Accessed 27 Dec 2016
24. Abbott A, Nandeibam S, O'Shea L (2013) Recycling: social norms and warm-glow revisited. Ecol Econ 90:10–18
25. Hage O, Söderholm P, Berglund C (2009) Norms and economic motivation in household recycling: empirical evidence from Sweden. Resour Conserv Recycl 53:155–165
26. Lange F, Brückner C, Kröger B, et al (2014) Wasting ways: perceived distance to the recycling facilities predicts pro-environmental behavior. Resour Conserv Recycl 92:246–254
27. Cantner J (1999) Ökonomische Besonderheiten des Entsorgungsmarktes (Economic characteristics of the disposal market). In: Bilitewski B, Schnurer H, Zeschmar-Lahl B (eds) Müllhandbuch. Kz. 1502, Lfg. 6/99. Erich Schmidt, Berlin
28. Geyer R, Kuczenski B, Zink T, et al (2015) Common misconceptions about recycling. J Ind Ecol 20(5):1010–1017
29. Wilson DC, Velis C, Cheeseman C (2006) Role of informal sector recycling in waste management in developing countries. Habitat Int 30:797–808
30. Cavé J (2014) Who owns urban waste? Appropriation conflicts in emerging countries. Waste Manag Res 32(9):813–821
31. Velis C, Wilson DC, Rocca O, et al (2012) An analytical framework and tool ('*InteRa*') for integrating the informal recycling sector in waste and resource management systems in developing countries. Waste Manag Res 30(9S):43–66
32. Fei F, Qu L, Wen Z, et al (2016) How to integrate the informal recycling system into municipal solid waste management in developing countries: based on a China's case in Suzhou urban area. Resour Conserv Recycl 110:74–86
33. Schüler K (2015) Aufkommen und Verwertung von Verpackungsabfällen in Deutschland im Jahr 2012 (Revenue and utilization of packaging waste in Germany in 2012) (Ed.: Umweltbundesamt) UBA-Texte 50/2015. http://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/texte_50_2015_verpackungsabfaelle_2012.pdf. Accessed 15 Dec 2016
34. Scharff H (2014) Landfill reduction experience in The Netherlands. Waste Manag 34:2218–2224
35. Umweltbundesamt (2016) http://www.umweltbundesamt.de/daten/abfall-kreislaufwirtschaft/entsorgung-verwertung-ausgewaehlter-abfallarten/altpapier#textpart-1. Accessed 14 Dec 2016
36. Seidemann C, Meinl G (2016) Entwicklung von Werkzeugen für Anlagenkonzepte zur Altpapiertrockensortierung mit neuen Produktzielen (Developing tools to derive plant concepts for the dry sorting of paper for recycling with new product aims). PTS-Forschungsbericht 30/15, Munich 2016. www.ptspaper.de
37. Hoornweg D, Bhada-Tata P (2012) What a waste. A global review of solid waste management. World Bank. www.worldbank.org
38. Deutscher Bundestag (2012) Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträglichen Bewirtschaftung von Abfällen (Law to promote recycling and to ensure environmentally sound waste management). http://www.gesetze-im-internet.de/bundesrecht/krwg/gesamt.pdf. Accessed 17 Dec 2016
39. Wagner J, Friege H, Séché M (2016) Evaluierung der Praxis gewerblicher Sammlung mit Blick auf die Anforderungen des hochwertigen Recyclings und der Wettbewerbsfähigkeit (Ed.: Umweltbundesamt), UBA-Texte 31/2016. http://www.umweltbundesamt.de/publikationen/evaluierung-der-praxisgewerblicher-sammlung-blick. Accessed 16 Dec 2016
40. Friege H, Dornack C, Friege N, et al (2015) Vermarktungschancen und Probleme bei der Vergärung von Bioabfällen aus Siedlungsabfall (Marketing opportunities and problems with the fermentation of biowaste from municipal waste). Müll Abfall 47(8):452–456

41. Kranert M, Gottschall R (2016) Einflussgrößen auf die separate Bioguterfassung unter besonderer Berücksichtigung der Qualität (Variables influencing separate collection of biowaste with respect to quality). Ed.: EdDE e.V., Cologne
42. OECD (2001) Responsibility: a guidance manual for governments. OECD Publishing, Paris. doi:10.1787/9789264189867-en
43. Lifset L, Atasu A, Tojo N (2013) Extended producer responsibility: national, international, and practical perspectives. J Ind Ecol 17(2):162–166
44. Atasu A, Subramanian R (2012) Extended producer responsibility for e-waste: individual or collective producer responsibility? Prod Oper Manage 21(6):1042–1059
45. Cahill R, Grimes SM, Wilson DC (2011) Extended producer responsibility for packaging waste and WEEE – a comparison of implementation and the role of local authorities across Europe. Waste Manag Res 29(5):455–479
46. Umweltbundesamt (2016) http://www.umweltbundesamt.de/daten/abfall-kreislaufwirtschaft/abfallaufkommen#textpart-3. Accessed 16 Dec 2016
47. Reh K, Franke M, Baum HG et al (2014) Vergleichende Analyse der Entsorgung von Verpackungsabfällen aus haushaltsnahen Anfallstellen auf der Basis der Verpackungsverordnungen in Deutschland und Österreich (Comparative study of the management of packaging waste from households based on the legal regulations in Germany and Austria). Ed.: ÖWAV Heft 169, Vienna
48. Baum HG (2014) Neuausrichtung der Verpackungsentsorgung unter Beachtung einer nachhaltigen Kreislaufwirtschaft (Realignment of packaging waste, taking into account sustainable environmental management). VKU, Berlin/Fulda
49. Friege H, Siepelmeyer H, Hofmann T, et al (2016) Fehlbefüllung von Biotonnen und ihre Ursachen. Erkenntnisse aus einem transdisziplinären Projekt in Lüneburg (Incorrect filling of biotopes and their causes. Findings from a transdisciplinary project in Lüneburg). Müll Abfall 48(12):641–645
50. Zhang DQ, Tan SK, Gersberg RM (2010) Municipal solid waste management in China: status, problems and challenges. J Environ Manage 91:1623–1633
51. Keramitsoglou KM, Tsagarakis KP (2013) Public participation in designing a recycling scheme towards maximum public acceptance. Resour Conserv Recycl 70:55–67

The Waste Management System in Qingdao City: Example for Modern Chinese Waste Management

Yingjie Sun and Weihua Li

Abstract Qingdao is an important economic center in eastern coastal China. With the rapid urbanization process, problems of municipal solid waste (MSW) management have become a new concern for the government. In Qingdao, MSW collection and transportation (MSW-CT) amounts increased from 0.81×10^6 t/a in 1999 to 1.85×10^6 t/a in 2015. The per capita MSW production was nearly 1.1 kg/(capita·d), higher than the Chinese average value of 0.70 kg/(capita·d). The MSW management system of Qingdao was dominated by the "Municipal Public Bureau of Qingdao." Due to the continuous reform of the sanitation management system, an operation mechanism of separation for government and enterprise, unified management, orderly competition and a three-level management system of "City – District – Street" were established. MSW-CT mode was mainly based on the combination of "multi-way collection in early, transfer station compression in late" and "compression car direct transport." MSW treatment was mainly located at the "XiaoJianXi Solid Waste Comprehensive Disposal plant of Qingdao," including sanitary landfill, incineration, composting, and recycling. Qingdao was one of the earliest pilot cities of MSW source separation in China. Although some relevant achievements were achieved, many problems were also found. In the future, MSW source separation will be regarded as a key concern for government departments in Qingdao. MSW management of Qingdao had always been leading position in the Shandong Province. However, some problems cannot be ignored, such as multi-head management, inadequate market competition, and inconsistent power between supervision and law enforcement. In the future, Qingdao's MSW management will be improved through structural reform, financial investment, and an increase in market competition and public environmental awareness. A "Qingdao model" in Chinese MSW management will be gradually established.

Y.J. Sun (✉) and W.H. Li
School of Environmental and Municipal Engineering, Qingdao University of Technology, Qingdao 266033, China
e-mail: yjsun1971@126.com

R. Maletz et al. (eds.), *Source Separation and Recycling*,
Hdb Env Chem (2018) 63: 31–64, DOI 10.1007/698_2017_25,

© Springer International Publishing AG 2017, Published online: 29 April 2017

Keywords Management, Municipal solid waste (MSW), Problem, Qingdao City, Source separation, Treatment

Contents

Abbreviations

LCV	Low calorific value
MSW	Municipal solid waste
MSW-CC	MSW classification collection
MSW-CT	MSW collection and transportation
$MSW_{p\text{-}c}$	Per capita MSW production
MSW-TT	MSW transportation and treatment

1 Introduction

With the rapid urbanization process, municipal solid waste (MSW) disposal has become a more and more serious problem. The prevention and control of MSW pollution is supposed to be the key environmental protection project in the near future. At present, at the national level, “Reduction, Resource, Harmlessness” of MSW is regarded as the basic principle of waste pollution prevention in the “Law on Environmental Protection” and “Law on Solid Waste Pollution Prevention and Control” of China. In addition, “Regulations on the Management of City Appearance and Environmental Sanitation,” “Measures for the Management of MSW,” “Notice on the Implementation of MSW Disposal Charging System to Promote Industrialization of MSW Disposal,” and other related technical standards on MSW incineration, landfill, etc., also provide specific measures for MSW pollution prevention. At the local level, provinces, municipalities, and regions also formulated a relevant local regulatory system based on the situation of local MSW generation and pollution. These national and local laws and regulations jointly built a legal system on pollution prevention and the control of MSW in China [1].

In the past, relevant departments have been committing to Qingdao’s waste management. However, there are still some problems: “inadequate financial investment, a poor financing channel, an imperfect management structure, and problems of timeliness, scientificity, and normalization.” Although “Clean Production Law” and “Measures for MSW Management” have been promulgated, there are still a lot of legislative blanks for MSW management in China. Moreover, in this field, other problems like “unobvious market economic regulation, not strict environmental law enforcement, weak environmental awareness of residents” also need to be further analyzed and explored.

Shandong is one of the biggest provinces in economy and population, with a high level of urbanization within the 23 provinces of China. By the end of 2014, the urban population in Shandong Province was 53.85×10^6 people, and the production amounts for MSW transportation and treatment (MSW-TT) were more than 9.59×10^6 t/a [2]. Shandong Province has been facing a positive response to national requirements and its own actual situation. In recent years, a series of laws and regulations on MSW management including “Technical Specification for Urban Environmental Sanitation Planning,” “Development Planning of MSW Disposal,” and “Measures for Management of Urban Appearance and Environmental Sanitation” have been formulated. Qingdao City, as a bigger city of economy and population in Shandong Province, is also an important economic center in China’s eastern coastal city. As a “National Health City,” it has been in the forefront of national environmental health management. Recently, Qingdao has developed some management systems such as “Measures for Management of Urban Appearance and Environmental Sanitation,” “Notice on MSW Charge,” and “Measures for Supervision and Administration on MSW Transportation and Treatment.”. In 2013, “Measures for MSW Classification Management” and “Work Plan to Strengthen MSW Classification” were formulated to further strengthen management of the

MSW classification collection (MSW-CC). As such, Qingdao has become the first city to set up special regulations on MSW-CC in Shandong Province.

The MSW management system is an integrated network for MSW "Generation – Classification – Collection – Transportation – Treatment." Therefore, it is necessary to analyze the status of MSW production, transportation, management, and treatment in a typical city in China. In order to find out the shortcomings of our MSW management system, we need to compare relevant systems both in China and abroad. The pollution status of MSW is in urgent need of alleviation in China. In this paper, the MSW management system of Qingdao is analyzed in the aspects of MSW generation, characteristics, transportation, management, and treatment. In addition, the MSW management mode of China was summarized as "from the spot to the surface," and solutions for the main problems of Qingdao's MSW management were proposed. Based on this system, the comprehensive "Qingdao model" was analyzed in order to map out the advantages and disadvantages in the modern Chinese waste management system.

2 General Situation of Qingdao

Qingdao is an eastern coastal city in China, located between latitude 35°35′–37°09′ and longitude 119°30′–121′00. It faces the Yellow Sea on the east and south. It faces North Korea, South Korea, and Japan across the sea (Fig. 1). The city area is 11,282 km^2, of which 3,257 km^2 is urban area.

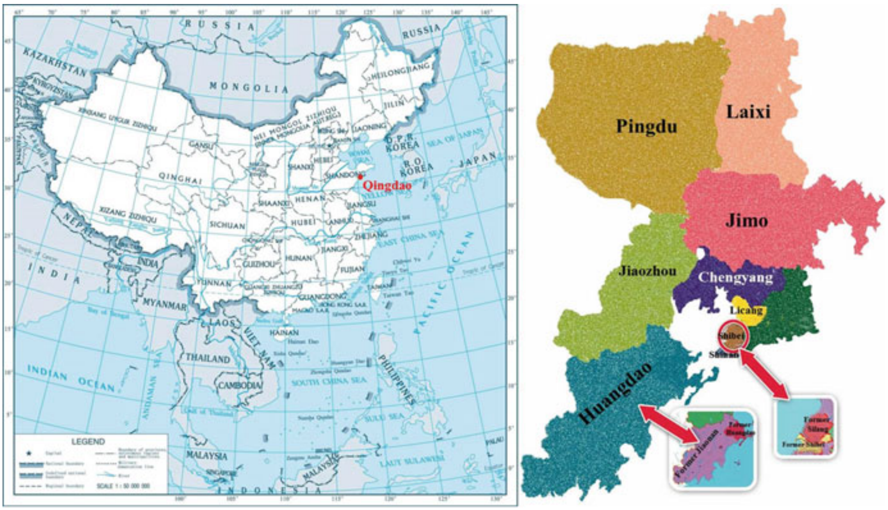

Fig. 1 Geographical position and administrative division of Qingdao City. Note: Related images from the "Qingdao government network" (http://www.qingdao.gov.cn/n172/)

As a hilly city, approximately 40.6% of the total area of Qingdao is highland and lowland. The total continental coastline in Qingdao is 730.64 km long and accounts for a quarter of Shandong Province's total coastal area. The total coastline in Qingdao amounts to 862.64 km if the island's coasts are considered together, which passes through 32 bays and encircles 69 islands.

Qingdao has beautiful scenery and a pleasant climate, and is famous in China for its delicious fresh seafood. Qingdao has a northern temperate zone monsoon climate with the characteristics of a marine climate, such as moist air, abundant rainfall, and four distinct seasons. It is neither hot in summer nor too cold in winter. The annual average temperature is 12.7°C. The hottest and coldest months are August and January, with average temperatures of 25°C and 1.3°C, respectively.

There are six urban districts (Shinan, Shibei, Licang, Laoshan, Chengyang, and Huangdao) and four county-level cities (Jiaozhou, Jimo, Pingdu, and Laixi) under the administrative division of Qingdao (Fig. 1). By the end of 2015, the total population of Qingdao and the urban population comprised 9.1×10^6 and 4.9×10^6 people [3].

By the end of 2015, the total production value in Qiangdao was 135.45 billion dollars. The gross domestic product (GDP) per capita reached 14,931.40 dollars. Centering on building a modern industrial system of "blue, high-end, rising," Qingdao has formed seven industrial bases, including "home appliance electronics, petrochemical chemicals, automobiles and locomotives, ship marine engineering, textiles and garments, food and beverages, and machinery steel" [3].

3 Waste Sector in Qingdao

According to statistics issued by the sanitation departments of Qingdao, around 1.85×10^6 tons of MSW were collected and transported in 2015. The MSW was mainly collected from residents, enterprises, hotels and restaurants, public places, and the farmers' market, which accounted for 56%, 14%, 5%, and 25%, respectively [4].

3.1 MSW Production Amounts in Qingdao

Due to the complex composition and varying properties, the characteristics of MSW were dependent on geographical location, climatic conditions, energy structure, socioeconomic level, consumption level of residents, living habits, and so on [5]. Figure 2 shows the variation of MSW and population in the urban district of Qingdao during 1999–2015, and the per capita MSW production ($MSW_{p\text{-}c}$) of the typical cities in China is shown in Fig. 3.

From Fig. 2, MSW production amounts increased gradually with the expansion of urbanization. After the implementation of new administrative divisions in 2013,

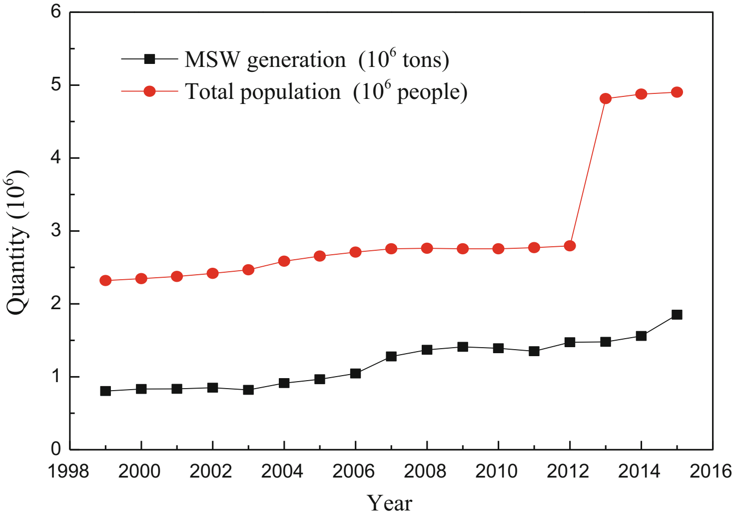

Fig. 2 Variations of MSW production and total population in Qingdao (1999–2015). Note: Related statistics of MSW production and total population refer to the data of the urban district of Qingdao. The statistics in 1999–2012 include: Shinan, Shibei, Sifang, Chengyang, Licang, Laoshan, Huangdao District. The statistics in 2013–2015 include: Shinan, Shibei (including the former Shibei and Sifang District), Chengyang, Licang, Laoshan, Huangdao District (including the former Huangdao District and Jiaonan City)

the total urban population increased rapidly due to the incorporation of Jiaonan City. This brought out the rapid increase in MSW production between 2013 and 2015. It can be predicted that in the coming years, the amount of MSW production will increase rapidly with the continuous increase in urban population.

As shown in Fig. 3, there are 8 cities where $MSW_{p\text{-}c}$ was greater than 1.0 kg/(capita·d) within 12 cities. The $MSW_{p\text{-}c}$ value in Qingdao is approximately 1.1 kg/(capita·d), which is similar to that of Beijing, Wuhan, Ningxia, Xi'an, and Nanjing. This result is consistent with the analysis of small areas (including commercial and residential) by Qingdao Environmental Health Sciences Research. Shanghai has a maximum $MSW_{p\text{-}c}$, of about 1.6 kg/(capita·d). Ningxia, Guangzhou, and Changsha have a similar result of 1.3 kg/(capita·d). Chongqing and Ji'nan have a minimum of 0.5 and 0.7 kg/(capita·d), respectively. In the actual calculation process, the statistical data of populations only included the urban resident population, while the urban flow population and foreign population were not taken into account. In addition, the degree of contrast between the floating population and permanent residents, and the differences in the statistical level, varied from city to city. Therefore, it is inevitable that there is a greater error in the calculation of $MSW_{p\text{-}c}$.

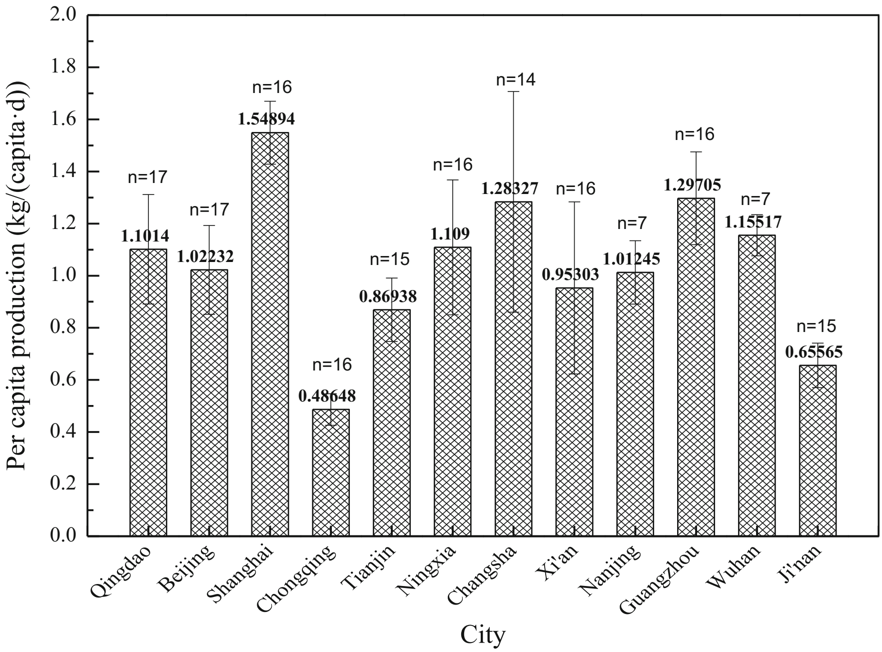

Fig. 3 Comparison of $MSW_{p\text{-}c}$ in selected Chinese cities (1999–2015). Note: Related statistical data from the "Statistical information network" and "Statistical yearbook" of the cities mentioned in 1999–2015. "n" refers to the number of data used in every city. During 1999–2014, Chinese $MSW_{p\text{-}c}$ was approximately 0.7 ± 0.05 kg/(capita·d)

3.2 Variation of MSW Components

Since 1989, 20 representative points from four districts (Shinan, Shibei, Sifang (now Shibei), Licang) have been selected for waste composition analysis by Qingdao Environmental Health Sciences Research. Figures 4 and 5 describe the changing trend of the MSW component in Qingdao from 1994 to 2016 by using different classification criteria. Figure 4a shows the physical composition of MSW in 2000–2009. The change in organic waste/kitchen waste (including: plant, animal, and shell), from 2000 to 2009, was individually plotted for further analysis (Fig. 4b) [6].

As shown in Fig. 4, organic waste (kitchen waste) was the main component of MSW in Qingdao, which accounted for 60–70%. The kitchen waste included plant, animal, and shell waste, and their content was stable during 2000–2009. The content of animal and shell waste was relatively small, and was basically steady at around 5%. The content of plants was at maximum approximately 60%. Moreover, the content of coal ash and soil has a downward trend, and paper has an upward trend. In addition, there was an unobvious variation for other wastes which had less content, below 4%.

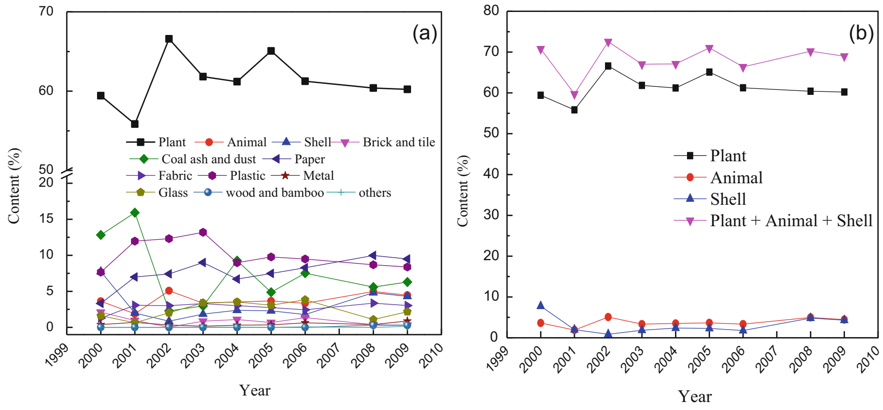

Fig. 4 Variation of MSW physical component in Qingdao City (2000–2009). (**a**) The change of detailed physical composition of MSW; (**b**) the change of the organic waste/kitchen waste (including: plant, animal, and shell). Note: Related statistical data from the research of Qu [6]

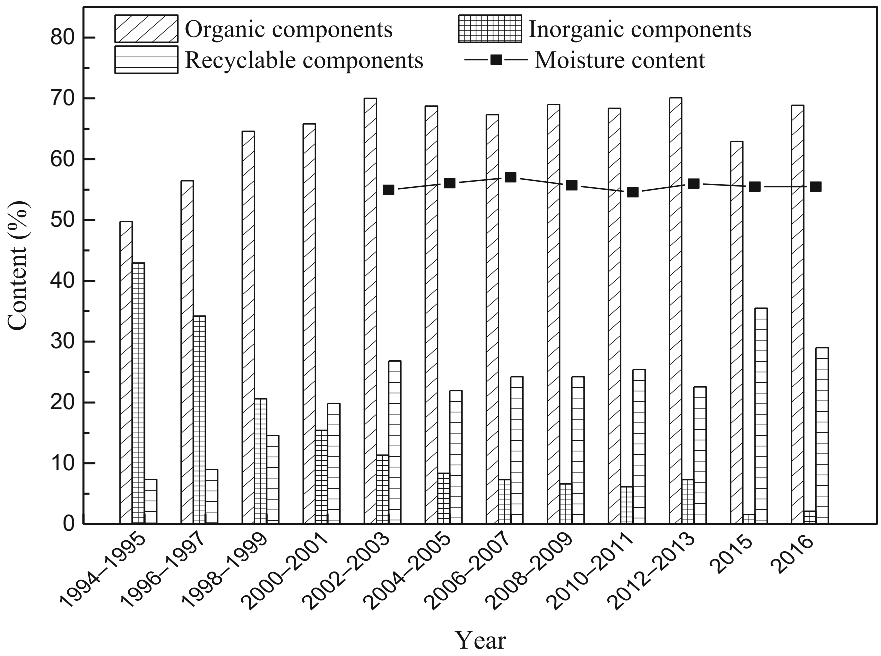

Fig. 5 Variation of MSW component in the city of Qingdao (1994–2016). Note: Related statistical data from the research of Qu [6] and "Environmental Sanitation Administrative Department of Qingdao" from 1994 to 2016

From Fig. 5, we can conclude as follows:

1. Organic components, including kitchen waste, peelings, and old food, are the main components, which show an increasing trend. As the main perishable materials, MSW will produce a certain amount of leachate and odor during the collection and disposal processes.
2. With the increase in the utilization ratio of central heating and natural gas, the content of inorganic dust and other wastes is gradually reduced, and the corresponding calorific value increased significantly. However, the moisture content is still high (approximately 55%), and some pretreatment measures are necessary to reduce water content before the MSW incineration.
3. With the development of the social economy and the improvement of people's living standards, recyclable components will increase greatly, and it will be beneficial to the work of MSW-CC in the future.

3.3 *Variation in the Physical and Chemical Properties of MSW*

The physical and chemical properties are based on the composition of MSW. These basic data are not only beneficial for the choice of MSW disposal mode and the construction of MSW disposal facilities, but also for the effective management of MSW. The physical and chemical properties of MSW are affected by MSW components, sampling location, storage time before analysis, and other factors.

3.3.1 Physical Property

Table 1 summarizes the experimental results of MSW physical properties in the main urban area (including Shinan, Shibei, Sifang (now Shibei), and Licang District).

Table 1 shows that there is a small fluctuation in the bulk density of MSW in the four seasons, varied in the range of 269.4–291.0 kg/m^3, and the average value was 280.9 kg/m^3. The variation in moisture content varied from 48.9 to 66.1%, and the average value was 56.0%, which was higher in the summer and lower in the winter.

Table 1 Physical and chemical properties of MSW in the main urban areas of Qingdao

Season	Bulk density (kg/m^3)	Moisture content (%)	Low-caloric value (kJ/kg, wet base)	Ash content (%, dry base)
Spring	287.9	48.9	5,800	38.0
Summer	269.4	60.2	4,349	21.0
Autumn	279.2	66.1	3,965	17.4
Winter	291.0	52.5	5,442	23.9
Average	280.9	56.0	4,889	25.1

The "sampling MSW" was taken directly from bins (garbage cans), and thus the moisture content of the "sampling MSW" will be a little higher than that of the actual MSW in the landfill, which will be compacted during the collection and transfer processes. The low calorific value of MSW (MSW-LCV) varied from 3,965 to 5,800 kJ/kg, and the average value was 4,889 kJ/kg. The ash content of MSW was about 17–38%, the maximum and minimum were found in the spring and autumn, respectively, and the average value was 25.1%. This was related to the high amount of coal ash produced by winter heating in some areas.

3.3.2 Element Content Variations

Element content is an important factor for the MSW incineration process, and the relative element content for MSW is shown in Table 2.

Table 2 shows that the total nitrogen content of MSW in Qingdao is slightly higher compared to other cities, with an average value of 2.53%. It may be a result of the higher content of kitchen waste that came from the developed catering industry [7]. This result is consistent with the investigation of physical components. Small percentages of chlorine (0.21%) and sulfur elements (0.42%) are contained in Qingdao's MSW, and their seasonal changes are tiny. However, chlorine and sulfur are two elements which are liable to cause the formation of dioxin and acid rain. So, it is necessary to strengthen the treatment of MSW incinerator flue gas to prevent secondary pollution.

3.3.3 Calorific Value

Figure 6 shows that the MSW-LCV in Qingdao has a large seasonal fluctuation. There is a gap of nearly 50% between the peak and valley value. It found that the minimum of MSW-LCV appeared in the third quarter. Overall, the variation of MSW-LCV was opposite to that of moisture content. In the future, with the

Table 2 Content of chemical elements of MSW in the main urban areas of Qingdao

City	Season	Element					
		C	H	O	N	S	Cl
		(%, dry base)					
Qingdao	Spring	30.98	3.99	20.80	2.12	0.35	0.20
	Summer	35.08	4.88	21.49	2.73	0.49	0.21
	Autumn	39.14	5.43	24.63	3.33	0.52	0.24
	Winter	32.68	4.43	18.94	2.48	0.43	0.19
	Average	33.58	4.50	21.31	2.53	0.42	0.21
Shenzhen	Average	35.97	4.63	24.31	0.33	0.23	0.31
Chengdu	Average	/	/	/	1.69	/	/
Chongqing	Average	31.63	4.55	22.67	1.24	0.15	0.30

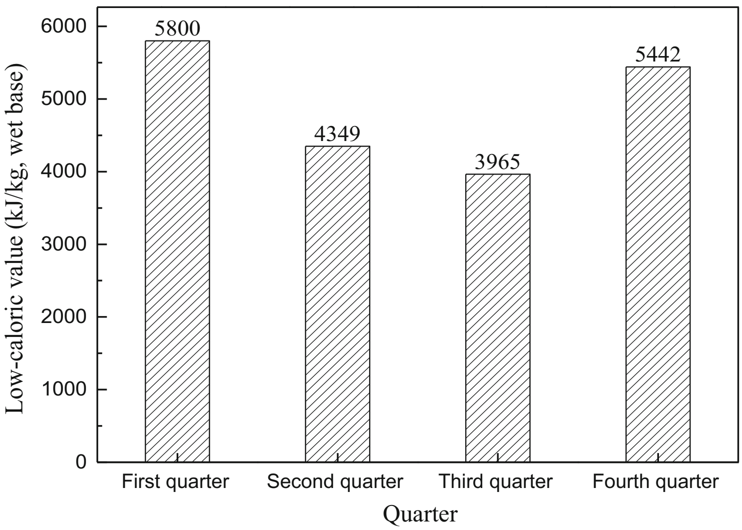

Fig. 6 Seasonal variation of low calorific value in the main urban areas of Qingdao

improvement of living conditions for residents, the heating method will be dominated by central heating. As a result, the dust content of MSW will be reduced gradually and MSW-LCV will be increased gradually. Then, the moisture content will be the main factor affecting MSW-LCV.

In other words, "urban planning, residents' living standards, fuel structure, and living habits" are important factors affecting the amount and characteristics of MSW. At present, the utilization rate of natural gas and coal gas in household cooking and heating water has approached 100%, and the residential area of Qingdao was artificially divided into "non-coal" and "semi-coal" areas according to fuel structure. The non-coal area is mainly some new residential areas on behalf of developed new areas with nicer facilities and relatively high living standards. The semi-coal area represents some areas in which the facilities and living standards are relatively backward. The differences in MSW characteristics between the non-coal and semi-coal area are shown in Fig. 7 and Table 3.

Based on previous investigation and analysis and combined with Fig. 7 and Table 3, there was a significant difference in some characteristics of MSW in non-coal and semi-coal areas. The plant content in non-coal areas was 9% higher than that of semi-coal areas. There was a higher quantity of "coal ash and dust" (5.17%) in semi-coal areas due to the burning of coal than non-coal areas (0.60%). The MSW-LCV of non-coal areas (5,082 kJ/kg) was nearly 20% higher than that of semi-coal areas (4,393 kJ/kg), which is a great difference. This shows that fuel structure is also an important factor affecting MSW composition. The MSW-LCV in the non-coal area was slightly higher than the calorific value requirements of 5,000 kJ/kg in "Standard for construction project of MSW incineration treatment project." It can be directly used to burn. In semi-coal areas, the content of "coal ash

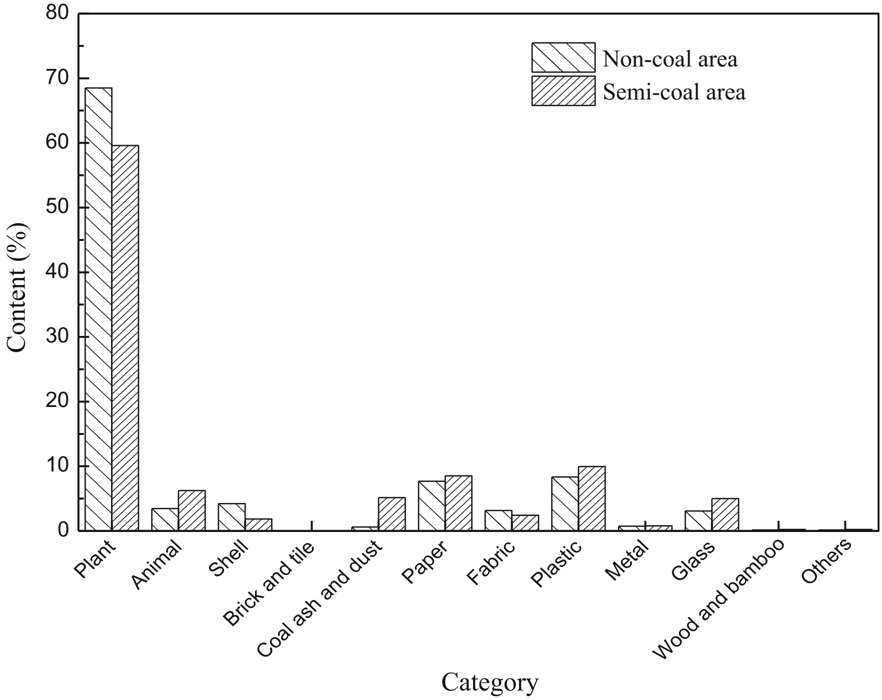

Fig. 7 Comparison of MSW physical components in non-coal and semi-coal areas of Qingdao

Table 3 Comparison of MSW characteristics in non-coal and semi-coal areas of Qingdao

Area	Bulk density (kg/m^3)	Moisture content (%)	Low-caloric value (kJ/kg, wet base)
Non-coal	197	57.03	5,082
Semi-coal	204	57.53	4,393

and dust" was correspondingly higher, especially in winter, which also influences MSW-LCV. Therefore, under the same conditions, the incineration of MSW in semi-coal areas will cost more.

3.4 Variation of MSW Production Amounts in Different Districts (Space)

As shown in Fig. 8, Laoshan and Huangdao Districts had greater $MSW_{p\text{-}c}$ values, which reached 2.5 and 2.0 kg/(capita·d), respectively. These values are significantly higher than the average value of 1.1 kg/(capita·d). Due to the shortage of statistics of floating and rural populations, the statistical $MSW_{p\text{-}c}$ values may be higher than

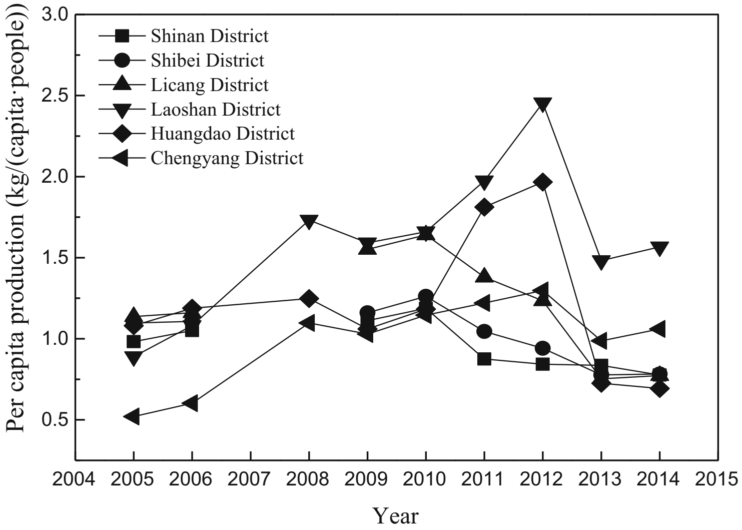

Fig. 8 Variation of $MSW_{p\text{-}c}$ in different district of Qingdao (2005–2014). Note: Relevant data are from the "Statistical Information Network" and "Research Institute of Environmental Sanitation" of Qingdao

the actual amounts. After 2012, the $MSW_{p\text{-}c}$ data showed a declining trend, which can be attributed to the confusion of MSW statistical data collection, and transportation (MSW-CT) and population in urban and rural areas. After the implementation of the new administrative division of Qingdao, the actual $MSW_{p\text{-}c}$ values in every district of Qingdao were in the range of 1.0–1.2 kg/(capita·d) according to official statistics.

4 Status of MSW Management in Qingdao

4.1 Main Management Institutions and Functions

Due to the continuous reform of the city sanitation management system, the operational mechanism of the separation of government and enterprise, and unified management, orderly competition was gradually established. A three-level management system mentioned as "City, District and Street" was formed.

At present, the collection, transportation, treatment, and disposal of MSW; formulation and implementation of related policy in sanitation industry; supervision of environmental sanitation and MSW treatment; and preparation of industry development planning are also managed jointly by the "Municipal Public Bureau of

Qingdao." It contains 11 departments. The main functions of every department are as follows:

1. The "District Sanitation Department" is responsible for organizing MSW-CT, the unified deployment and terminal management of MSW are charged by "Municipal Waste Management Department."
2. The "Urban Administration Bureau," the city's environmental health administrative department, is responsible for the management of related enterprises in MSW-TT.
3. The "Management Center of City Appearance and Environmental Sanitation" and "Urban Management/Construction Bureau" are commissioned by the "Environmental Sanitation Administrative Department," responsible for daily management, supervision, and guidance of related MSW disposal enterprises.
4. The "Urban Management Law Enforcement Bureau" has the right to exercise punishment related to the environmental health administration, also responsible for the inspection and handling of illegal activities of related enterprises in MSW-TT.

Relevant departments and authorities did their own duties and played their own roles, established a digital control platform, and realized the real-time online monitoring of MSW transport vehicles and treatment enterprises.

4.2 Main Management Systems and Policies

4.2.1 Main Management Systems and Policies for MSW-TT

To strengthen supervision and management for related industries of MSW-TT, according to relevant laws and regulations and Qingdao's situation, the "Urban Administration Bureau" and "Environmental Protection Bureau" formulated "Interim Measures for Supervision and Management of MSW-TT." The main contents are as follows:

1. The enterprises engaged in MSW-TT should obtain a service license authorized by related departments. Relevant enterprises must accept and dispose of MSW in accordance with related regulations. The industrial waste, medical waste, electronic waste, other toxic and hazardous waste, and construction waste shall not to be allowed.
2. The supervision and management department are required to have clear job rules and responsibilities to ensure the safe and stable operation of related enterprises.

4.2.2 Main Management Systems and Policies for MSW Charge

Since 2003, the "Municipal Public Bureau of Qingdao" constantly improved the charge system of MSW, and accordingly, the toll service center and charge platform of "POS intelligent reading management system" were established. The implementation of charge systems of "Unit – Charge – System" for MSW treatment, "One – Card – Pass" for public utilities, improved the city environment and achieved remarkable social and economic benefits. A series of systems related to the MSW charge were also developed in every district of Qingdao between 2006 and 2012. For example, a notice on carrying out a charging system for MSW disposal was issued by the "Municipal Price Bureau of Qingdao" in 2012.

4.2.3 Pilot Project of MSW-CC

In 2013, relevant departments studied and formulated "Management Measures for MSW-CC" and the "Implementation Plan for Strengthening MSW-CC." Its aims were to further strengthen and promote "classification management, source reduction, recycling and harmless disposal" of MSW in Qingdao. Herein, Qingdao became the first city to set up special regulations for MSW-CC in Shandong Province. The legislation experience of Beijing and Guangzhou was referred by "Management Measures for MSW-CC" of Qingdao. The definition, category, and method of MSW-CC, the responsibility and obligation of related departments were also regulated. MSW was divided into six categories as "Management Measures," including kitchen waste, hazardous waste, recyclable waste, decoration waste, large waste, and other wastes.

5 Overview of MSW Comprehensive Treatment System in Qingdao

5.1 Technical Route of MSW Treatment

Before 1999, Qingdao did not have a special MSW management institution or treatment area, and all MSW was simply dumped into landfills. This process did not take any measures in terms of environmental protection. Eventually, the potential environmental and health risks occurred due to the release of methane gas, leachate, and odor during landfilling processes.

In order to improve the living environment of Qingdao; to achieve comprehensive benefits for the environment, ecology, and society, a "Solid Waste Disposal Co., Ltd" was established. It included the "Solid Waste Transfer Station of Taiyuan Road" (now located in LouShanHe) and "XiaoJianXi Solid Waste Comprehensive Disposal Site of Qingdao." This company was mainly responsible for MSW collection, transportation, compression, and disposal. Based on the principle of "harmless as basis, reduction as focus, and re-utilization as expand," the MSW treatment system of Qingdao was formed (Fig. 9).

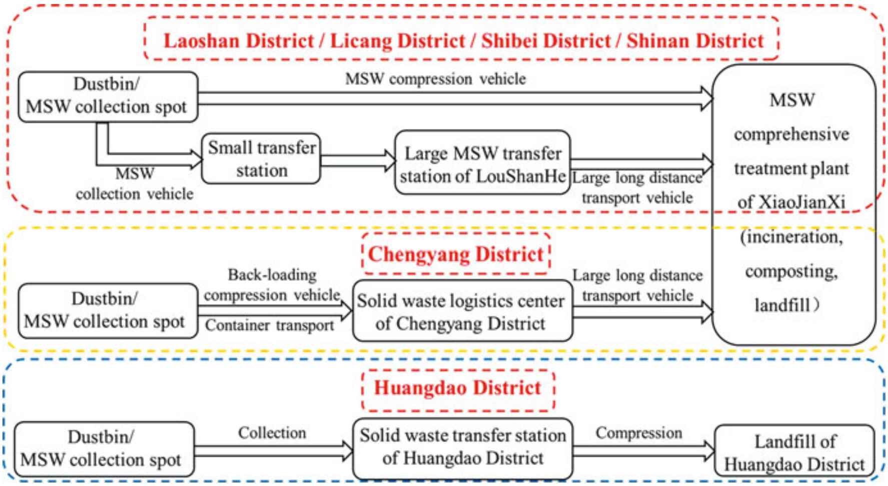

Fig. 9 MSW collection – transportation – treatment system in the urban district of Qingdao. Note: Relevant information was provided by the Municipal Public Bureau of Qingdao et al. [8]

5.2 MSW-CT System

5.2.1 Status of MSW-CT System in Qingdao

The MSW-CT of the urban district is supervised and managed by the environmental sanitation department, mainly responsible for the secondary compression of MSW in the large transfer station. The district sanitation department is responsible for MSW-CT in their respective areas. MSW in all districts is collected and transported to the “Comprehensive Treatment Plant of XiaoJianxi.”

There are two large MSW transfer stations in the urban district of Qingdao, “Large MSW Transfer Station of LouShanHe” (4,000 t/d) and “Solid Waste Logistics Center of Chengyang District” (550 t/d), respectively. In addition, there are 47 small MSW compression transfer stations, and 85 hanging dragon type MSW transfer stations. The “Transfer Station of Laoshan District” will be built in the near future. In addition, there is one large MSW transfer station in the Huangdao District, the “Solid Waste Transfer Station of Huangdao District” (1,000 t/d). The transport vehicles of the urban district are mainly MSW collection/compression trucks, a hook arm car, and other types of compression cars.

The MSW-CT mode included the combination of “multi-way collection in early and compression transfer of interchange station in late” as the main, and “compression car direct transport” as the auxiliary. The detailed MSW-CT mode in every district was shown in Fig. 9.

5.2.2 Planning of the MSW-CT System in Qingdao

Considering the principle of environmental priority, the MSW-CT of the urban district will enable the new planning model in the future: "MSW collection spot (dustbin) – primary transportation to the small scale compression transfer station – secondary transportation to the large scale compression transfer station-MSW incineration power plant in XiaoJianXi" (Fig. 10). The area near XiaoJianXi can adopt a simplified MSW-CT mode: "MSW collection spot (dustbin) – primary transportation to the small-scale compression transfer station – MSW incineration power plant in XiaoJianXi."

5.2.3 Introduction of the MSW Transfer Station in Qingdao

Large-Scale MSW Transfer Station in LouShanHe

The LouShanHe transfer station is located in the Licang District and its adjacent "Sewage Treatment Plant of LouShan River." The distance is about 10 and 35 km from the urban district and the "XiaoJianxi MSW comprehensive treatment plant," respectively. The main function of this transfer station was MSW transfer (4,000 t/d), bulky waste disposal (50 t/d), and a temporary emergency workshop with a storage capacity of 12,000 tons.

Fig. 11 shows the technical flow of this transfer station. The technology of "vertical compression transfer" was adopted in the process of MSW transfer (Fig. 12). Bulky waste was disposed of with "crushing and magnetic separation technology." The combination technology of the "membrane bioreactor

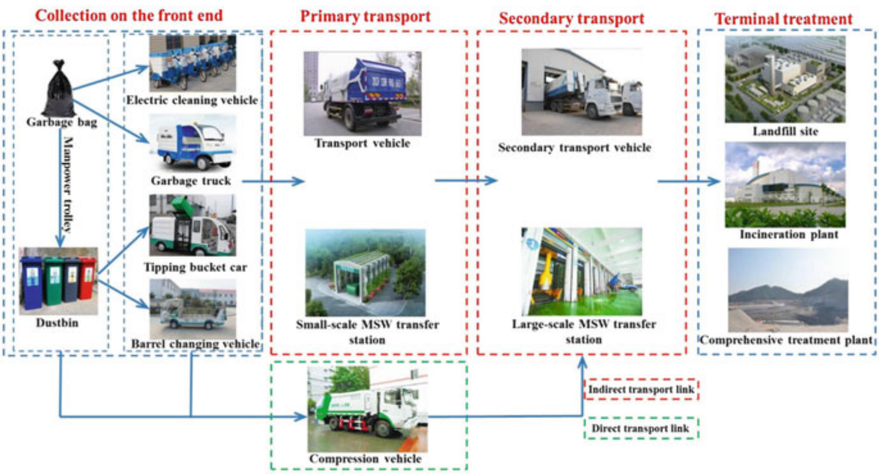

Fig. 10 Schematic diagram of the MSW secondary transportation mode in Qingdao. Note: Relevant information was provided by the Municipal Public Bureau of Qingdao et al. [8]

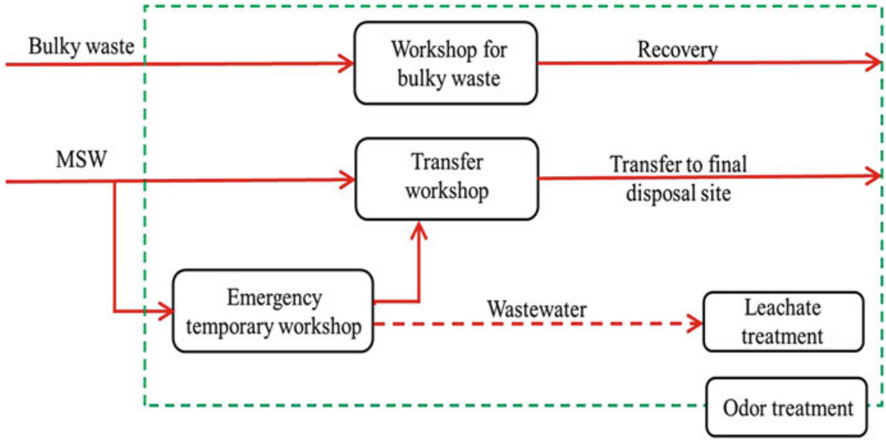

Fig. 11 Technical route of MSW transfer station of LouShanHe. Note: Relevant information was provided by the "Large MSW Transfer Station of LouShanHe"

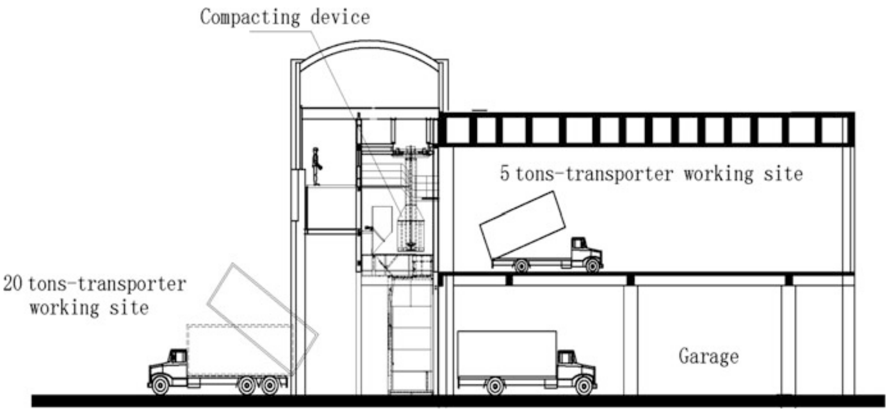

Fig. 12 Schematic of vertical compression transfer technology. Note: The figure was provided by the "Large MSW Transfer Station of LouShanHe"

(MBR) + nanofiltration" was used for leachate treatment. The combination technology of "plant liquid spray + biological deodorant" was applied as a deodorant.

Solid Waste Logistics Center of Chengyang District

The solid waste logistics center of Chengyang is located in the Chengyang District (Fig. 13). The main technology for MSW transfer was similar to the "LouShanHe MSW transfer station." The distance is about 25 km from the "XiaoJianXi MSW comprehensive treatment plant." The construction scale was 550 t/d, and the main

Fig. 13 Image of the solid waste logistics center of the Chengyang District. Note: This image was provided by the Municipal Public Bureau of Qingdao et al. [8]

function was the transportation of MSW from the Chengyang District to the "MSW comprehensive treatment plant of XiaoJianXi."

Solid Waste Transfer Station of the Huangdao District

The project mainly includes three parts: the MSW transfer area (7,600 m^2), the life services area (5,000 m^2), and the maintenance logistics support area (3,000 m^2) (Fig. 14). It covers a total construction area of about 29,600 m^2, and with a total investment of 16.00 million dollars. The designed transfer capacity of MSW was 1,000 t/d, which began to operate in 2014. Its services cover the daily collection of MSW in the Huangdao District. It can meet the transport demand of the Huangdao District in the next 10–15 years. The equipment for this project was introduced from Holland, ranking at the internationally advanced level. The service function of the project mainly consists of five parts: automatic central control, hermetic type, automatic compression, automatic biological deodorant, and automatic dust collection.

5.3 MSW Treatment System

There are four facilities for the terminal treatment of MSW (Fig. 15, Table 4) with a total treatment capacity of 3,936 t/d, including two sanitary landfills, one incineration power plant, and one composting (biochemical treatment) plant. The harmless

Fig. 14 Image of the Solid Waste Transfer Station of the Huangdao District. Note: The image was provided by the "Solid Waste Transfer Station of Huangdao District"

treatment rate of MSW is reached at 100%, and the resource processing rate is reached at 50%.

It is located in the north of XiaoJianXi village in the Chengyang District (Fig. 15). The land area of planning was 9.38×10^6 m^2. Ten construction projects were planned initially, and it has built and run five projects. They include a sanitary landfill (7.20×10^6 m^3), an incineration power plant (MSW treatment capacity: 1,500 t/d; installed capacity: 30 MW), a composting plant (MSW: 150 t/d; sludge: 150 t/d), a landfill leachate treatment plant (750 t/d), and a landfill gas power plant (with an installed capacity: 3.03 MW). At present, the comprehensive treatment plant takes nearly 90% of the task of the urban MSW disposal. In 2015, the treatment capacity for various waste, municipal sludge, and leachate was 1.62×10^6 tons, respectively. In addition, the amount of electricity generation and fertilizer production was 20×10^6 kWh and 25,000 tons, respectively. In the near future, another five projects will be built, including a sanitary landfill (secondary phase: i.e., secondary phase construction project), an expansion project of a leachate treatment plant, an incineration power plant (secondary phase), a kitchen waste treatment plant, and a resource utilization project for incineration residue.

According to the plan, by the end of 2020, the comprehensive MSW treatment capacity of the whole urban area will reach more than 5,000 t/d. At that time, the MSW comprehensive treatment system of "Incineration power as main, Biochemical treatment as auxiliary, Sanitary landfill as safeguard" will be formed. The harmless treatment rate of MSW will stay at 100%, the resource efficiency will be more than 90%, and the goal of MSW zero-landfill and recycling sustainable development will basically be realized [8].

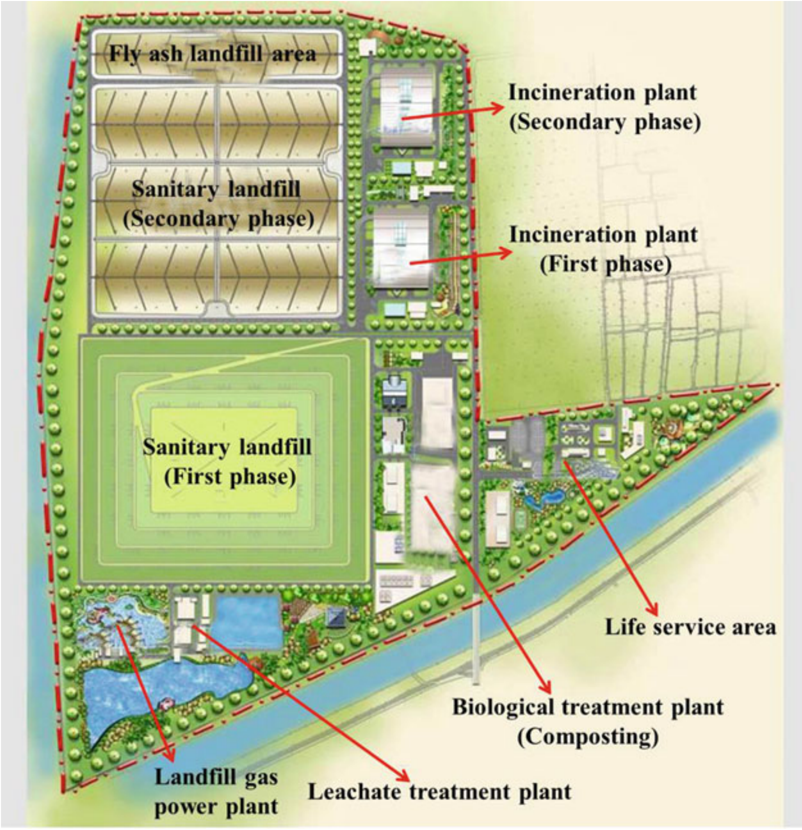

Fig. 15 MSW comprehensive treatment plant of XiaoJianXi in Qingdao. Note: Relevant information was provided by the "Solid Waste Disposal Co., Ltd of Qingdao"

Table 4 List of MSW disposal facilities in the urban district of Qingdao

Disposal facility		Scope of service	Design treatment capacity (t/d)
MSW comprehensive treatment plant of XiaoJianXi	Sanitary landfill site	Shinan, Shibei, Licang, Chengyang, Laoshan District	1,500
	Incineration power plant		1,500
	Composting plant		300
Sanitary landfill of Huangdao		Huangdao District	636

Note: Relevant statistical information was provided by the Municipal Public Bureau of Qingdao et al. [8]

5.3.1 MSW Sanitary Landfill of XiaoJianXi

1. First phase of the project (Fig. 16): It covers an area of 0.66×10^6 m^2, a landfill reservoir area of 0.27×10^6 m^2 with a total capacity of 7.20×10^6 m^3, with a total investment of 34.90 million dollars. The main function is responsible for urban MSW treatment in Qingdao. The landfill site has an internationally advanced impervious system, a leachate collection and treatment system, and a landfill gas collection and utilization system, which is one of the first harmless landfill sites identified by the "Ministry of Housing and Urban-Rural Development."
2. Secondary phase of the project (plan to build): It is located on the north side of the first phase landfill site. It will cover a proposed area of 0.37×10^6 m^2. It includes a landfill area for MSW, and a storage area for fly ash. A total investment of 45.10 million dollars has been estimated. The landfill capacity of MSW and fly ash is 3.74×10^6 m^3 and 0.78×10^6 m^3, respectively. Its service life is about 20 years.

5.3.2 MSW Incineration Power Plant of XiaoJianXi

1. First project phase (Fig. 17): It covers an area of about 58×10^3 m^2, with a total construction area of 35.3×10^3 m^2, and a total investment of 98.90 million dollars. The designed MSW incineration treatment capacity is 1,500 and 550×10^3 t/a, respectively. The assembly capacity of the generator is 30 MW.

Fig. 16 Effect picture of the sanitary landfill site of XiaoJianXi. Note: The image was provided by the "Solid Waste Disposal Co., Ltd of Qingdao"

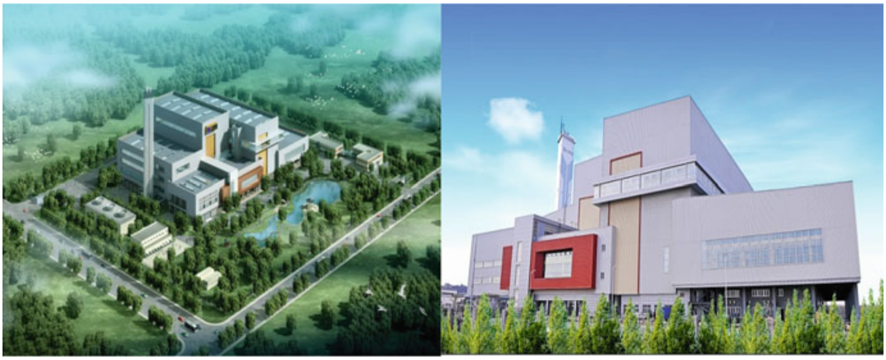

Fig. 17 MSW incineration power plant of XiaoJianXi. Note: The images were provided by the "Environment Renewable Energy Co., Ltd of Qingdao"

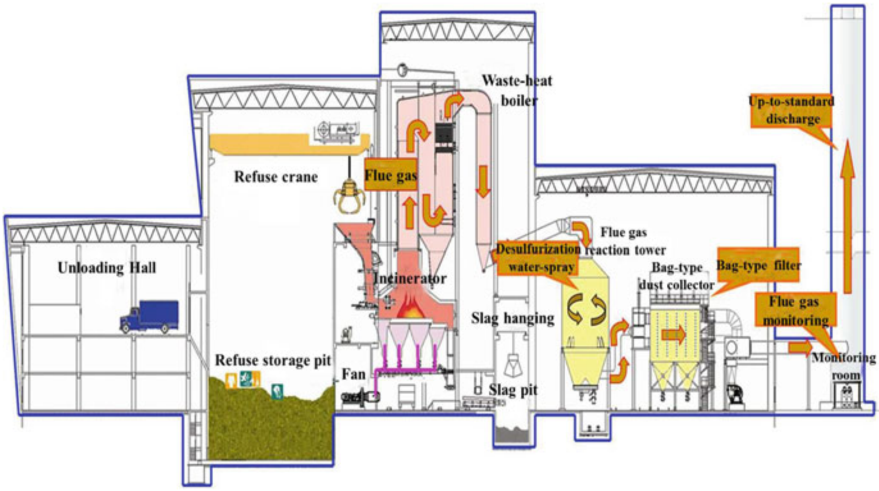

Fig. 18 Process flowchart of MSW incineration power plant of XiaoJianXi. Note: The image was provided by the "Environment Renewable Energy Co., Ltd of Qingdao"

The generation power and access network power is 200×10^6 and 157×10^6 kWh/year, respectively. The "Build – Operate – Transfer (BOT)" operation mode was applied to this project. The major emissions targets have met European secondary stage exhaust emission standards (Waste Incineration Directive 2000). The main process of the incineration system is shown in Fig. 18. The slag produced by MSW incineration was reused. The exhaust gas required the removal of nitrogen, acid, dust, dioxin, heavy metals, and other hazardous substances before standard discharge. The fly ash produced by MSW incineration was processed at the "Landfill site of XiaoJianXi" after stabilization treatment. The landfill leachate was sent to "Leachate treatment plant of XiaoJianXi."

2. Secondary project phase (plan to build): A “Co-disposal of MSW and sludge incineration power plant” will be the second project phase, which will cover an area of about 80×10^3 m^2. The designed treatment amounts of MSW and sludge (moisture content $<80\%$) are 1,500 and 350 t/d, respectively. The “mechanical reciprocating grate furnace” will be applied at the incineration of MSW and sludge. The sludge will be mixed incineration with MSW after drying with two “sludge dry lines,” and there will be two “incineration production lines.” The combination incineration process of “SNCR + rotary spray semi-dry deacidification + dry jet + activated carbon injection + bag filter + flue gas recirculation” will be adopted. Meanwhile, the SCR system will be reserved. This project was recommended by the “Ministry of Finance of China” as the third batch demonstration project of government and social capital cooperation. It will invest about 123.60 million dollars, and operate in a “Public – Private – Partnership (PPP)” mode with a cooperation period of 30 years.

5.3.3 MSW Composting (Biochemical Treatment) Plant of XiaoJianXi

The total project investment was 18.50 million dollars, with a designed treatment capacity of 300 t/d (Fig. 19). The main function of the project was used for the treatment of mixed waste with high organic content (such as kitchen waste sourced from the classification collection of household waste). The compost products can be used for landscaping and mountain restoration. The “mechanical manual sorting + tunnel-type dynamic high temperature aerobic biochemical treatment”

Fig. 19 Panoramic view of the composting (biochemical treatment) plant of XiaoJianXi. Note: The image was provided by the “MSW biochemical treatment plant of XiaoJianXi”

Fig. 20 Compost fermentation room and compost product. Note: The images were provided by the "MSW biochemical treatment plant of XiaoJianXi"

was the main process technology in this project. The equipment of this plant was imported from Canada. The specific technological process is as follows: "Unloading – Rolling screen – Manual sorting – Fermentation room – Post processing – Compost products" (Fig. 20). In 2014, after the transformation of original equipment and technology, it can meet the requirements for sludge treatment. At present, both the treatment of MSW and municipal sludge reached 150 t/d.

5.3.4 Landfill Leachate Treatment Plant of XiaoJianXi

1. First project phase: The total investment in this project was 16.00 million dollars, and the design treatment capacity of landfill leachate was 900 t/d. The main treatment process of this project was "Membrane bioreactor (MBR) + Reverse osmosis + Biological filter" (Fig. 21). The standard of "first-level A" of "Integrated Wastewater Discharge Standards of China" was demanded for effluent quality. The effluent met the requirements for domestic water. More than 90% of the effluent for use in production and greening water came from the "Reclaimed Water System." The project was chosen as a demonstration project for municipal science and technology by the "Ministry of Housing and Urban-Rural Development" in 2012.
2. Second project phase (planning to build): It is located on the west side of the first project phase. It is estimated to be a total investment of 33.40 million dollars with a total area of 45.8×10^3 m^2, and the designed treatment capacity is 1,000 m^3/d. The combination process of "MBR + Disk-tube reverse osmosis" will be adopted for the treatment of leachate wastewater. In addition, the treatment scale for concentrated leachate from the RO membrane unit is 500 m^3/d, and the processing technology of "Pretreatment + Low energy consumption mechanical evaporation" will be adopted accordingly.

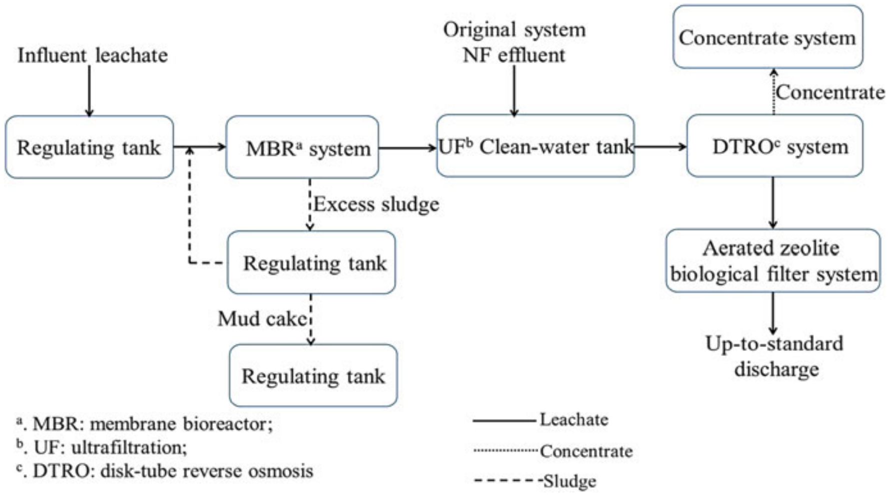

Fig. 21 Process flow diagram of the landfill leachate treatment plant of XiaoJianXi. Note: The process flow diagram was provided by the "Landfill leachate treatment plant of XiaoJianXi"

Fig. 22 Picture of the landfill gas power plant of XiaoJianXi. Note: The images were provided by the "DongJiang Environmental Renewable Energy Co., Ltd of Qingdao"

5.3.5 Landfill Gas Power Plant of XiaoJianXi

The project for landfill gas recycling involved an investment of about 8.72 million dollars, and the assembly capacity of the generator is 3.06 MW with an annual power generation of 20×10^6 kWh (Fig. 22). The "Build – Operate – Own (BOO)" operation mode was taken into account for this project with a franchise period of 12 years. During the operation period, 200×10^6 kWh power will be generated, and

1.50×10^6 tons of CO_2 gas will be consumed. The main flow for this technology is as follows: "Landfill gas – Gas pretreatment system (dehumidification and purification) – Internal combustion generating set (generate electricity) – State Grid Corporation of China." The excrescent gas was transported to a "flare system" and incinerated for harmless treatment.

5.4 Planning of MSW Treatment Facilities in Qingdao

According to the status of MSW treatment in Qingdao, the disposal facilities scheduled to be built are shown in Table 5.

6 Status and Problems with MSW-CC (MSW Source Separation) in Qingdao

6.1 Status of MSW-CC Pilot

Qingdao is one of the earliest cities to carry out MSW-CC in China. In 2011, one enterprise and institution, one school, one market, and one closed residential area were selected as a pilot area in Shinan, Shibei, Sifang (now Shibei), and the Licang District, respectively. Recyclable waste, kitchen waste, and other wastes were classified in accordance with the classification criteria in the pilot area. Then, the work of "classification, collection, transportation, and treatment" was carried out by sanitation departments and renewable resource recycling enterprises. Although MSW-CC in the pilot areas has achieved some results, there is no denying that there are some shortcomings, for example, related to staff that was not on duty, the classification level of residents is out of conformity, etc.

After 2012, relevant departments of Qingdao, according to the "Implementation Plan of MSW-CC," began to do related work step by step. With the idea from its

Table 5 Phased construction plan of disposal facilities in Qingdao

No.	Disposal facility	Scale	2016	2017
1	MSW sanitary landfill of XiaoJianXi (secondary phase)	4.52×10^6 m^3	Construction	
2	MSW incineration power plant of XiaoJianXi (secondary phase)	1,500 t/d	Plan	Construction
3	MSW incineration power plant of XiaoJianXi (third phase)	1,500 t/d	Plan	Plan
4	Large MSW transfer station of Laoshan District	750 t/d	Plan	

Note: Relevant information was provided by the Municipal Public Bureau of Qingdao et al. [8]

parts to the whole territorial responsibility, social participation was the main principle. With the plan to 2020, the comprehensive classification system based on "Throw – Collection – Transportation – Treatment" will be initially established, and it will be expected to achieve a leading level in China.

6.2 Problems and Reasons in MSW-CC

In order to deeply understand the obstacles and reasons of MSW-CC in Qingdao, we conducted a survey by visiting several areas of the first batch pilots in 2012. According to the method of simple random sampling, a total of 800 questionnaires were issued to the densely populated area, and 720 questionnaires were collected, including 698 valid questionnaires. Based on the statistical results of the survey, we summarized the status of the MSW-CC and some opinions and suggestions on Qingdao's MSW-CC from residents.

6.2.1 Insufficient Promotion and Education

According to surveys, for residents, the way to hear about the knowledge of MSW-CC was mainly from TV, radio, internet media, and community publicity. All respondents have already realized the benefits of MSW-CC, which indicates that the concept of MSW-CC has been accepted by the public. Seven percentage of interviewees do not want to carry out the MSW classification because they found that the final treatment of MSW was still mixed, although they carried out the MSW classification in the pilot process.

From the investigation of "how to achieve MSW classification," the answer for most people is still obscurely that there is no real clear MSW classification knowledge for most residents. To a certain extent, it reflects that the promotion and education work of the MSW classification is not enough. Therefore, methods and knowledge about MSW-CC need to be implemented through relevant publicity work.

6.2.2 Classification Awareness is Higher, but Classification Habits Need to Be Developed

In the survey, 95% of interviewees knew the MSW classification, and they clearly stated that it had a positive effect on the environment. It indicates that most people have a sense of the MSW classification. However, the actual pilot work regarding MSW classification did not reach the expected target. In fact, it is caused by the deviation between people's consciousness and behavior. It was found that only less than 10% of interviewees had a habit of always putting garbage into sorting trash, while more than 60% of interviewees never had the habit. Therefore, public habits related to MSW classification need to be developed further.

6.2.3 Classification Facilities Are Imperfect, Classification Logo Is Unclear

In the survey, it was found that 70% of respondents believe that whether the classification facilities (bins) and classification logo of MSW are convenient/clear or not will affect their classification behavior. There was a series of problems, such as there was one color for the bins, and the number of bins was too many or too few. Moreover, some bins are too far from the living area in some residential areas. Therefore, imperfect or unclear MSW classification facilities or logo was a major reason for unsatisfactory MSW classification work.

6.2.4 Non-binding Measures for MSW Classification Work

The survey results showed that 82% of respondents think that MSW-CC is a conscious act, 90% respondents think that community and the recycling station should be responsible for MSW-CC, and less than 5% of respondents think that it should be attributed to individuals. For the behavior of non-compliance with MSW classification, 95% of respondents believe that it is an individual ethical issue, and only 5% of people think that it is a violation action. Therefore, the lack of mandatory constraints on the residents from relevant laws and regulations is also a major reason for unsatisfactory MSW classification in Qingdao. Countries like Japan and Germany that have an excellent legislative system for MSW-CC are worth noting in the future.

6.3 Related Work on MSW Classification Needs to Be Carried Out in the Future

In the near future, the research and demonstration work of the MSW-CC system will be completed, and the plan for promotion and education will be made. At the same time, the construction of relevant local rules and regulations about MSW-CC will be gradually carried out.

From 2017 to 2020, the number and scope of the pilot department and area will be gradually expanded and achieve full coverage of the urban MSW-CC eventually. The bins filled with kitchen waste will be set up independently. The kitchen waste will be transferred to the plant for treatment or composting. To further standardize the implementation of relevant measures, relevant supporting binding rules and regulations will be formulated. At that time, MSW-CC will be regarded as concerns

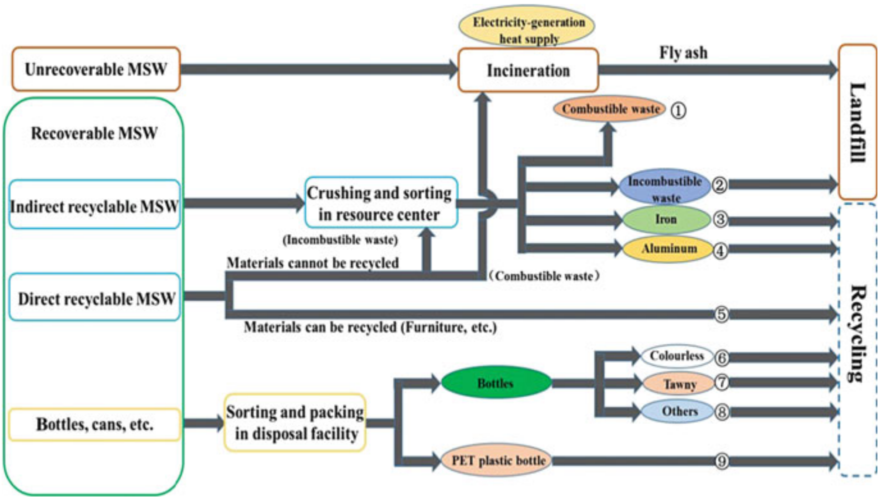

Fig. 23 Sketch map of MSW-CC in the long-term planning phase (after 2020). Note: Relevant information was provided by the Municipal Public Bureau of Qingdao et al. [8]

of environmental management. An implementation and supervision mechanism and a team related to MSW-CC will be established. Eventually, based on the accomplishment of this plan, the efficiency of MSW source separation and the goal of source reduction and resource utilization will be achieved gradually [8].

After 2020, according to the plan, MSW in each district will be divided into two major categories and four small categories. The major categories include recyclable and unrecyclable waste. The recyclable waste can be classified into three categories, including indirect recyclable waste, direct recyclable waste, and bottles and cans. The waste can be resource recovered through nine categories (①–⑨ in Fig. 23).

7 Problems of the MSW Management System in Qingdao

7.1 *Inefficiency Management System: "Multi-Channel Management"*

The departments related to MSW management, supervision, and law enforcement include "Municipal Public Bureau," "Municipal Environmental Protection Bureau," and "District Construction Bureau" in Qingdao. The environmental sanitation management system/team in each district/city is complex and inflexible. It caused a situation of multichannel management in many departments and teams. The mode of multichannel management in the MSW management system has some disadvantages, such as poor coordination and confusion over responsibilities. It has brought about some losses in manpower, material resources, and financial capacity. Therefore, there is a big gap between the demands of the MSW management system and the requirements of industrialization and market development in Qingdao.

7.2 Non-uniform Supervision Power and Law Enforcement Power: "Inadequate Supervision"

The "Municipal Law Enforcement Bureau" is responsible for the administrative law enforcement for environmental health. The application of funds and the provision of personnel are distributed in every district. Nevertheless, the city sanitation department only has a responsibility for business guidance and supervision power. Therefore, the problems of separation of management and punishment and the weak timeliness of law enforcement power were gradually brought out. In addition, the shortages of staff in relevant departments, the inadequate work energy, the lower work standard, and the relatively backward environmental monitoring method were also likely to be the important factors that restricted environmental supervision.

7.3 Lack of Market Competition

Most of the sanitation operation departments in every district were basically affiliated with government. Market competition was obviously insufficient due to the lack of participation of social enterprises. Therefore, if there is no market mechanism as a guarantee, the efficiency of MSW management is difficult to improve. It is imperative to reform the current system of MSW management.

7.4 Larger Gap in Management Level

The overall management level of the central city is higher than the county-level city. There is a big gap between central and county-level cities at the MSW management level.

8 Conclusion and Prospects

In recent years, with the rapid development of China's urbanization and social economy, MSW management is becoming one of the key issues for national social and economic development. As an important economic center in eastern China, MSW management in Qingdao is a microcosm of China.

There is no doubt that the amounts of MSW will continuously increase in the future, particularly attributed to the urbanization and the collection of rural area refuse. The ratio of the organic component in MSW will increase slightly, which may be around 70%. The heat value will increase according to the increase in the organic component. The moisture content of MSW is an important factor affecting its further treatment, which results in a low heat value, difficulty and high-costs for leachate treatment.

Based on the characteristics of MSW, source separation and integrated management systems are necessary for MSW management. Source separation of MSW is not only a technical issue, which is related to the characteristic of MSW and the treatment facilities, but also a social and economic issue, which makes it difficult to resolve in a short time. A clear and economic separation standard, education of the public, separated transportation, and treatment are also necessary to accelerate the source separation work of MSW. Maybe it is necessary to strengthen the responsibility related to MSW separation for government, enterprises, and the public, which can obligate them to do the work well.

As for the integrated management system, apart from the collection and transportation, the biological treatment, i.e., composting and anaerobic digestion, incineration, and landfill, are all necessary. Based on the MSW source separation which should discuss the degrees of different treatment methods, this is also an argument in China. In the developed area of China, zero landfill of raw refuse and all-incineration are a planned goal of MSW treatment. Does source separation make the heat value of MSW decrease, which will influence the operation of incineration facilities? Will source separation make the quantities of MSW needing to be incinerated decrease sharply?

Local laws and regulations are important to promote the management level of MSW. Market participation is helpful for the improvement of MSW management.

MSW management is a complex issue, which involves technical, environmental, economic, and social factors. It should be based on not only the scientific method, but also the economic and social development level.

Acknowledgements We acknowledge the data and information support provided by the "Municipal Public Bureau of Qingdao," "Municipal Environmental Protection Bureau of Qingdao," "Solid Waste Disposal Co., Ltd of Qingdao," "Environment Renewable Energy Co., Ltd of Qingdao," "DongJiang Environmental Renewable Energy Co., Ltd of Qingdao," and other relevant sanitation departments for this article.

References

1. Liang Y (2010) Study on the improvement of city residential solid waste in Qingdao. Master degree dissertation, Shandong University of Science and Technology, Qingdao (in Chinese)
2. National Bureau of Statistics of the People's Republic of China (2016) Statistical yearbook of China 2015. China Statistics Press, Beijing. http://www.stats.gov.cn/tjsj/ndsj/2015/indexch.htm (in Chinese)

3. Qingdao Municipal Bureau of Statistics (2016) Statistical yearbook of Qingdao 2016. China Statistics Press, Beijing. http://www.stats-qd.gov.cn/statsqd/news/20169116055880851.shtml (in Chinese)
4. Jiang Z, Zhang WX, Qi WJ (2011) Physical properties and change regularity of domestic waste in Qingdao City. Environ Sanit Eng 19(3):36–37 (in Chinese)
5. Yang HF, Zhang Q (2004) Solid waste resource. Chemical Industry Press, Beijing (in Chinese)
6. Qu XZ (2011) Study on life cycle assessment of urban solid waste processing systems in Qingdao. Master degree dissertation, Qingdao University of Technology, Qingdao (in Chinese)
7. Zhang X (2015) Food waste treatment technology in Qingdao and study on operation management. Master degree dissertation, Qingdao University of Technology, Qingdao (in Chinese)
8. Municipal Public Bureau of Qingdao, Qingdao Municipal Institute of City Planning and Design, China Urban Construction Design & Research Institute (2014) The environmental sanitation plan of Qingdao City: instructions. Municipal Public Bureau of Qingdao Press, Qingdao (in Chinese)

Part II
Source Separation Technology and Opportunities

Separation by Manual Sorting at Home: State of the Art in Germany

A. Nassour, S. Hemidat, A. Lemke, A. Elnaas, and M. Nelles

Abstract Most developing and transitional economies are faced with daunting challenges related to household waste segregation, climate protection, environmentally compatible treatments and the utilisation of the various waste fractions.

Source separation has a major impact on the effectiveness of waste management systems, as it causes significant changes in the quantity and quality of waste that reaches final disposal, which is the main factor in the generation of the greenhouse gas, methane. This environmental impact can be significantly reduced by the separate collection and recycling/use of organic waste.

The German Closed Cycle Management Act is aimed at turning waste management into resource management. The realisation that waste can be a useful source of raw materials and energy is not new; metals, glass, organic waste and textiles have been collected before and put in to new use. The waste management policy, which has been adapted in Germany over the past 20 years, is based on closed cycles and assigns disposal responsibilities to the manufacturers and distributors of products. This has made people even more aware of the necessity to separate waste, has led to the introduction of new disposal technologies and increased recycling capacities (Nelles et al., Proc Environ Sci 35:6–14, 2016).

Nowadays, Germany has great experience in terms of waste separation. Around 14% of the raw materials used by German industry are recovered waste, thus leading to a reduction in extraction levels and the related environmental impact. Modern closed-cycle management contributes, with a share of approximately 20%, to achieving the German Kyoto targets for the reduction of climate-relevant emissions.

A. Nassour (✉), S. Hemidat, A. Lemke, A. Elnaas, and M. Nelles
Department of Waste Management and Material Flow, University of Rostock, Rostock 18051, Germany
e-mail: abdallah.nassour@uni-rostock.de

R. Maletz et al. (eds.), *Source Separation and Recycling*,
Hdb Env Chem (2018) 63: 67–88, DOI 10.1007/698_2017_26,
© Springer International Publishing AG 2017, Published online: 27 April 2017

Keywords Awareness, Bins, Collection, Germany, Household waste, Municipal solid waste, Recycling, Segregation

Contents

1 Development, Status and Prospects of the Waste Management System

Municipal waste includes waste from private households (domestic waste, bulky waste, biowaste, separately collected recyclables, such as glass, paper, packaging and metals), as well as industrial waste resembling household waste (waste from doctors' offices, administrative buildings, schools and kindergartens). Furthermore, municipal waste also includes market waste, road sweepings and litter, waste from public places, park waste and waste from water management measures (sewage sludge). Table 1 shows the waste generation balance in 2014 [1].

Germany implemented separate collections for waste, household and other kinds of waste more than 20 years ago. Diverse environmental damage, lack of landfill space and the use of finite resources led, in the early 1990s, to a rethink in waste management. Today, climate change and energy demand are important arguments for the separate collection and utilisation of all kinds of waste [2, 3].

The German Closed Cycle Management Act (Kreislaufwirtschaftsgesetz, KrWG) is aimed at turning waste management into resource management. The realisation that waste can be a useful source of raw materials and energy is not new; metals, glass, organic waste and textiles have been collected before and put to new use. The waste management policy, which has been adapted in Germany over the past 20 years, is based on closed cycles and assigns disposal responsibilities to the manufacturers and distributors of products. This has made people even more aware of the necessity to separate waste, led to the introduction of new disposal technologies and increased recycling capacities [4].

Today, 14% of the raw materials used by German industry are recovered waste, thus leading to a reduction in the extraction levels and related environmental

Table 1 Waste generation balance in Germany in 2014

Type of waste	Total quantity of waste generated	Of which: waste deposited in waste treatment plants with					Recovery rate
		Disposal operations			Recovery operations		
		Landfilling	Thermal disposal	Treatment for disposal	Energy recovery	Recycling	
	1,000 tons						100%
Total	400,953	71,383	9,457	4,497	39,351	276,265	79
Of which:							
Municipal wastes	51,102	123	4,765	1,117	11,553	33,544	88
Wastes resulting from mining and treatment of mineral resources	30,172	30,013	1	16	5	138	0
Construction and demolition wastes	209,538	23,478	130	1,055	1,467	183,407	88
Secondary wastes	50,633	4,615	1,718	750	15,028	28,523	86
Remaining wastes (in particular of manufacturing and other economic activities)	59,508	13,153	2,843	1,560	11,299	30,654	70

impact. Modern closed-cycle management contributes, with a share of approximately 20%, to achieving the German Kyoto targets for the reduction of climate-relevant emissions.

Closed-cycle management not only contributes to environmental protection, but it also pays economically. The waste management industry has become an extensive and powerful economic sector in Germany: almost 200,000 people are employed in approximately 3,000 companies that generate an annual turnover of approximately 40 billion euros. 15,000 installations contribute to resource efficiency through recycling and recovery procedures. High recycling rates of approximately 60% for municipal waste, 60% for commercial waste and 90% for construction and demolition waste speak for themselves [5].

The legal foundations for proper waste management were provided far back in history. With the Prussian local tax act of 1893, municipal finances were reorganised and the prerequisite for the establishment of municipal cleaning facilities was created. Municipalities were henceforth entitled to levy charges for waste disposal. Later, in 1935, the German municipal authorities established the general principles of collection and use of the waste collection system. This ensured the collection of all waste and forbids all illegal disposal routes. In the mid-1960s, cities and municipalities were finally identified as waste disposal authorities, and were thus responsible for waste disposal. During the same period, the first bulletins were drafted on the issue of waste disposal, which were the guidelines for dealing with waste.

However, waste management in Germany is constantly changing, due to new political and legal requirements as well as technical and organisational developments, and has developed into a large and powerful economic sector. Thus, modern waste management is the result of a long development process. Figure 1 summarises this development along a time axis [4].

1.1 From Waste Disposal to Recycling

Until the late 1960s, waste had mostly been deposited at one of the approximately 50,000 uncontrolled landfills. Only about 37% of the municipal waste was treated and deposited in one of the approximately 130 sanitary landfills, 16 composting plants and 30 incineration plants [6]. Back then, the technologies were not yet mature and caused secondary environmental problems: groundwater pollution from leachate and gas emissions due to the degradation of biogenic waste, pollutant emissions from waste incineration and quality problems of mixed waste compost.

In addition, economic growth in the early 1970s led to an increase in industrial production and private consumption, as well as disposable packaging and products. During this time, waste disposal had, on the one hand, to deal with the waste masses and, on the other hand, to develop an *orderly waste disposal* system, preventing any risk to human and animal health. The first constitutional legal framework, the 1972 Waste Disposal Act, should address both problems [4].

With this law, the number of the original 50,000 uncontrolled landfills was considerably reduced, while at the same time a continuous improvement in landfill technology could be achieved by the end of the 1980s. In the same period, the number of waste incineration plants increased, but still with insufficient flue gas cleaning. Although all the plants had dust removing facilities, only a third of the plants had an extended flue gas purification system. As a result of this, and due to the increasing share of chemical products in domestic waste, the quantities of emitted pollutants continued to rise.

The technologies for the treatment of mixed waste are not yet environmentally compatible. The first attempts to produce solid recovered fuel (SRF) have been discontinued, as there are major problems regarding emissions. Also, the composting of the municipal waste could not be implemented. As a result of the above-mentioned change in household waste composition with increasing proportions of metals and composite materials, the heavy metal loads increased. Because of the low quality, the compost was not accepted for use by farmers.

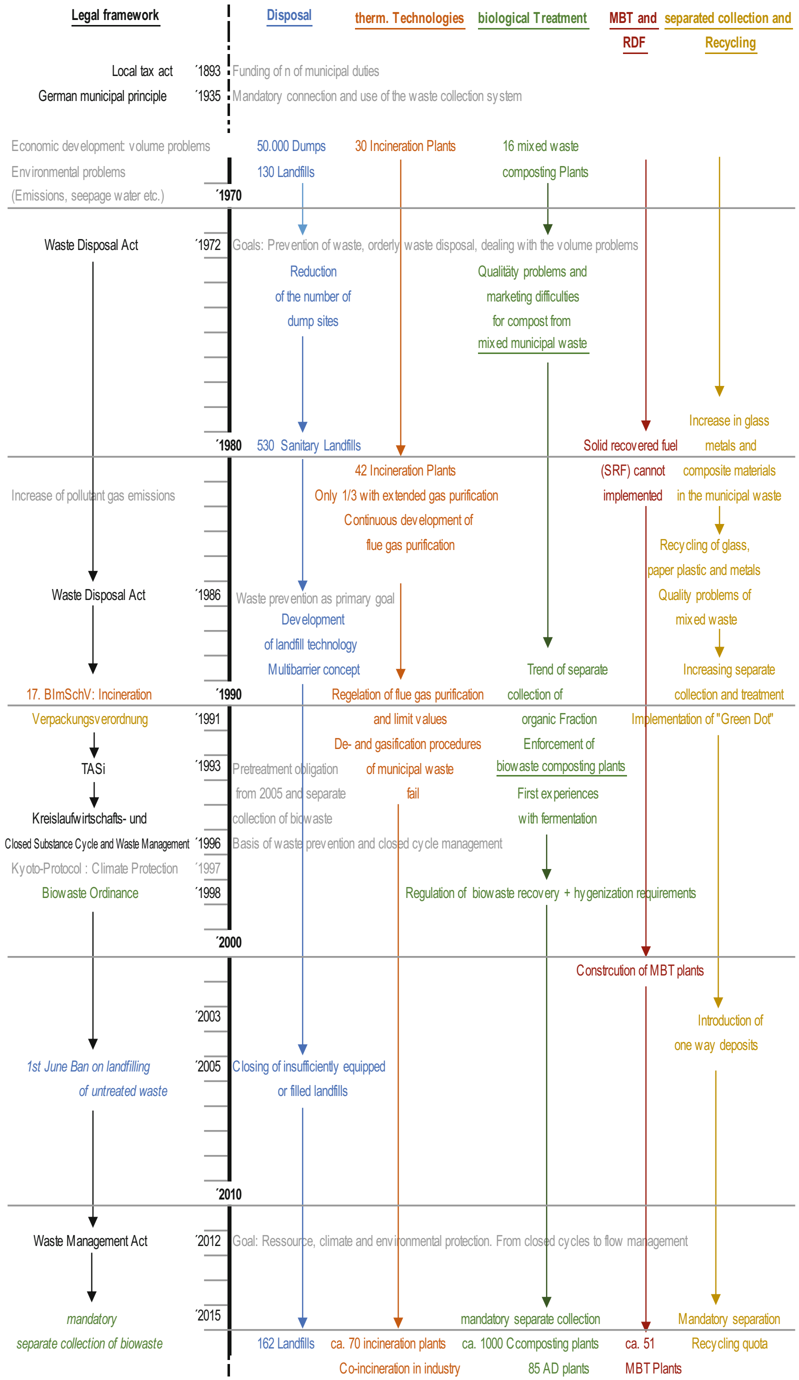

Fig. 1 Summary of the legal (*left*) and technical (*right*) development of waste management in Germany along a time axis (Source: [4])

The first attempts to recover recyclables from municipal waste failed. The reasons for that were, among others, the inadequate product quality and the poor efficiency of the sorting systems. From the mid-1980s onwards, individual municipal waste streams began to be separately collected (glass, paper).

While good progress has been made in the proper disposal of waste, only poor results were achieved in the management of waste quantities. For this reason, the *1986 Waste Act* declared the prevention of waste as a superior objective before recovery and disposal. Waste prevention includes low-waste technologies, the recycling of products and their recyclable construction, as well as the increase in their service life.

Due to the quality problems of the recovery technologies, a rethinking of the waste disposal routes took place at the beginning of the 1990s and the separate collections became more important. The collection of the biogenic fraction, separated from the rest of the municipal waste, was clearly increasing. Only from this separately collected biowaste could an economic product be produced. Composting of separately collected biowastes thus gained importance, as well as the anaerobic treatment of this fraction as an addition to composting, which was developing. Therefore, at the beginning of the 1990s, fewer than ten plants for mixed municipal waste composting and about eighty plants for biowaste composting were operated. At the same time, recycling, which mainly concentrated on glass, paper, plastic and metal, has proven that a separate collection of the valuable substances is the prerequisite for the production of high-quality secondary raw materials.

With the 17th Federal Emission Control Ordinance of 1990, existing waste incineration plants had to be upgraded with a sophisticated exhaust gas purification system or shut down, and the prescribed limit values had to be met. Despite this regulation, the incineration of waste was still disapproved by the population, as new pollutants such as dioxins became of concern. The 17th Federal Emission Control Ordinance is constantly revised, the exhaust gas purification systems are further upgraded and the quality of emissions from waste and waste co-incineration plants has greatly improved. Up until the 2000s, however, not only the number of plants, but also the average plant throughput increased. In the area of the thermal treatment of municipal waste, tests with degasification and gasification technologies have been conducted, which were, however, not accepted.

With the 1991 Packaging Ordinance, users and distributors were obliged to take back and recycle their product packaging, in accordance with the principle of ‘product responsibility’. The dual system (‘Green Dot’ symbol) was founded to fulfil this duty.

The multi-barrier concept was implemented in landfilling technology, and thus liquid and gaseous emissions were minimised. However, it is easy to see that, above all, the gaseous emissions were not completely prevented. In order to minimise the negative environmental impact of waste deposition, the pretreatment of waste became obligatory in 2005 with the Technical Instructions for Waste Management.

In 1996, the Waste Act was amended, forming the Closed Substance Cycle and Waste Management Act. In addition to waste prevention, the focus is on the recycling industry. In addition, the 1998 Biological Waste Ordinance regulates the quality requirements for the recycling of separately collected biogenic waste [4].

1.2 Climate and Resource Protection Are Gaining Importance

With the Kyoto Protocol in 1997, the issues of climate and resource protection are becoming more important. Thanks to the strict legal requirements, waste management is able to contribute significantly to climate protection. The methane formation in landfills was avoided, above all, by the ban on the deposition of untreated municipal waste, which was issued in June 2005. Also, the increased material and energy recovery from the waste contributes to climate and resource protection.

At the beginning of the 2000s, mechanical-biological waste treatment was developed, in addition to thermal waste treatment, in order to meet the pretreatment requirements. The 30th version of the Federal Emission Control Ordinance hereby regulates the technical standards to be met with regard to emissions. At first, the focus was on the input of the biogenic fraction. However, later on, the recovery of the high calorific fraction became more and more interesting. Through the energetic recovery of the waste, fossil fuels can be replaced.

In 1990, waste management still contributed to about 38 million tons of CO_2 equivalents, while in 2006 it was able to save about 18 million tons of CO_2 equivalents. From 1990 to 2006, waste management reduced its annual emissions of climate-damaging gases by approx. 56 million tons [7].

Furthermore, by 2005, most insufficiently equipped or filled landfills were shut down and the so-called one-way deposit was introduced.

In Germany, waste segregation is the answer to tackling several environmental problems arising from waste management. Since the biogenic fraction is mainly responsible for climate-relevant emissions, the segregated collection and treatment of this fraction has significantly reduced this environmental impact. The separate collection of biowaste is also a precondition for the production of high-quality composts and therefore, for the recirculation of organic matter and nutrients. Furthermore, the segregated collection of biogenic waste and its recycling reduces the amount and changes the composition of residual waste, reducing its water content. In this light, Fig. 2 summarises the different benefits achieved by the segregated collection of biogenic waste [4].

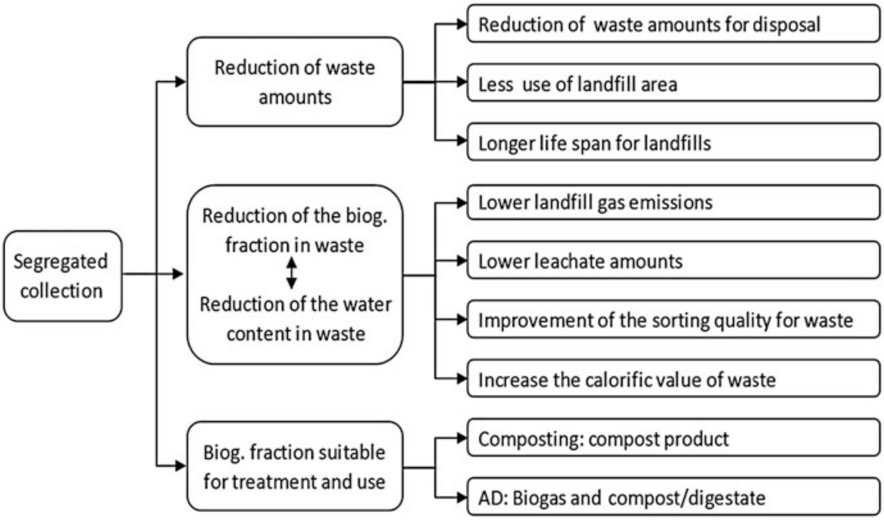

Fig. 2 Importance of segregated collection of biogenic waste for climate and resource protection (Source: [4])

1.3 Highest Global Recycling Rates: On the Path to Material Flow Management

The current version of the Waste Management Act of 2012 provides the path of the waste and closed-cycle management to a resource-efficient economy. The objective of waste management is to conserve natural resources and manage waste in an environmentally sound manner, so that a sustainable improvement in environmental and climate protection, as well as resource efficiency, is achieved. Waste is regarded as a valuable raw material whose effective use saves natural resources. While waste prevention leads to a reduction in raw material consumption and environmental pollution, waste recovery focuses on the recycling of raw materials and energy into the economic cycle.

The key to the Waste Management Act is the implementation of the five-stage waste hierarchy: waste prevention, reuse, recycling, other utilisation and finally, waste disposal. The best option with regard to environmental protection has always been a priority, even if technical, economic and social aspects are taken into account. This ensures a consistent focus on waste prevention and recycling.

The contribution of waste management to resource conservation is reflected in the world's highest recycling rates, which save raw materials and primary energy. Nearly 57% of municipal waste is recycled. For individual waste fractions, recycling rates are even higher, e.g. for packaging. In 2012, 96.3% (the requirement was 65%) of the total packaging waste was recovered, and 71.3% was recycled (the requirement was 55%).

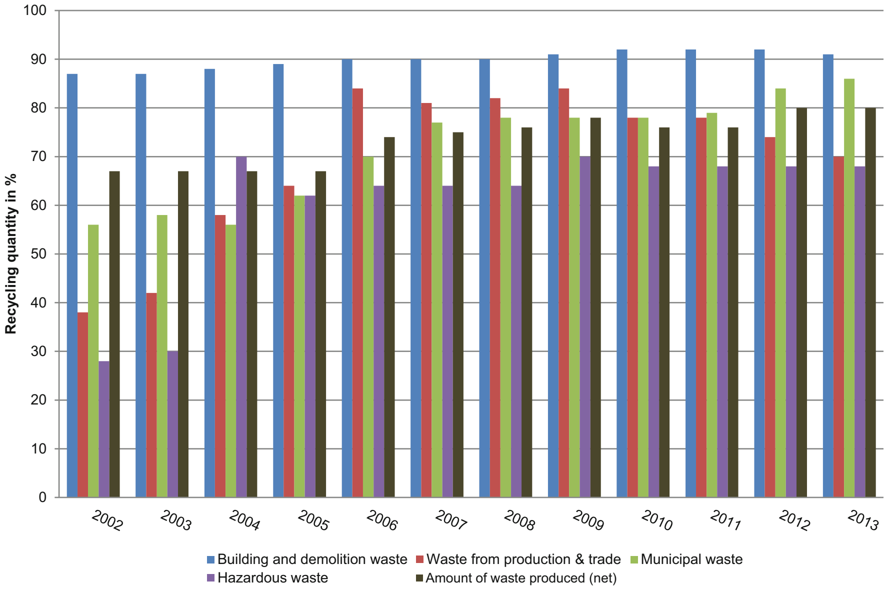

Fig. 3 Recycling amount of main waste streams along the time axis (Source: [8])

Further emissions reduction can also be achieved in the field of climate protection, for example, through the increase in capacity in mechanical-biological pretreatment.

The Waste Management Act continues the proven division of tasks between private and public waste management companies. According to the 'polluter pays' principle, commercial producers and the owners of waste are responsible for the disposal of their wastes. According to the principle of public services, municipalities are responsible for the disposal of waste from private households and from other areas of origin.

As a result, waste management in Germany has developed into a large and powerful economic sector with over 250,000 employees and an annual turnover of around 50 billion euros. New impulses are expected with the mandatory segregation of waste paper, waste glass, plastic waste and biogenic waste since 2015. Figure 3 shows the recycling amount of main waste streams in Germany [4].

1.4 *Innovative Waste Concepts and Technology Transfer for Resource and Climate Protection*

The future goal of the federal government is to further develop the waste and recycling industry into a sustainable resource-efficient material flow management. Thus, the substances and materials found in the waste are to be completely used up to supersede the landfilling of waste [9]. Figure 1 illustrated in Sect. 1.1 provides a summary of the legal and technical development of waste management in Germany.

In order to utilise the material potential of the various waste streams as fully as possible, and to meet the quality requirements, the separate collection and treatment of waste streams is essential. This is because the closed cycle system must ensure that pollutants from waste do not recur in new products, but are harmlessly discharged.

Waste management in Germany has reached a high technical level. For this reason, the federal government supports and promotes sustainable waste management concepts with modern and efficient waste treatment technologies, which can be used to extract raw materials or energy from the waste, as well as the transfer of knowledge and technologies.

2 Technical State of the Art for the Utilisation and Disposal of Biogenic Waste (from Separate Collection and Residual Waste)

In Germany, it is common to divide waste into different groups instead of throwing everything into the same bin. The reason is that separated waste is reusable. Therefore, waste is not only separated in residential houses and dormitories, but also on the whole campus area and at other public places, such as the train station.

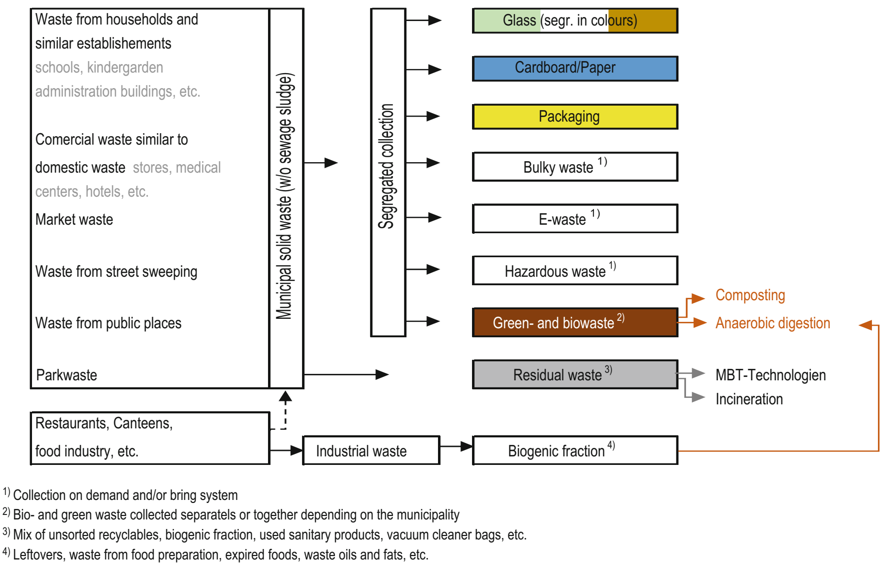

Fig. 4 Summary of sources of municipal solid waste and waste fractions collected separately (Source: [4])

In this context, Fig. 4 shows the different sources of municipal solid waste and the waste fractions collected separately in Germany [4].

Biogenic waste is one main fraction collected separately. Despite all the effort put into the segregated collection, an important quantity of biogenic waste is still contained in residual waste. Therefore, there are two main fractions of biogenic waste in municipal solid waste: a clean fraction separately collected, suitable for material recovery, and a mixed fraction in residual waste.

2.1 Legal Background and Importance for Resources and Climate Protection

For all municipal waste fractions, there are legal requirements as to how they are to be collected, transported, recycled or treated. German legislation on waste management is characterised by a large amount of European legislation. European directives must be transposed into national law.

The central directive is the *European Waste Framework Directive* (Directive 2008/98/EC), which contains important requirements for German waste law. Article 4 specifies a waste hierarchy that prioritises the long-term use of products (waste prevention and preparation for reuse); material recovery (recycling) comes in second. The recovery of energy is characterised as significantly inferior.

The long-term use of products and material recovery reduces the need for the energy-consuming and environmentally damaging production of new raw materials. Furthermore, energy recovery can make a sustainable contribution to resource and climate protection in terms of efficiency.

Article 8 grants extended producer responsibility to all those who develop, manufacture, process, sell or import products. This includes the withdrawal of used products and waste as well as financial responsibility for its sustainable exploitation. The goal is to improve reuse, prevention and recycling. Furthermore, the products should be reusable several times, be technically durable and, after they have become waste, be suitable for proper and harmless recovery and environmentally compatible disposal.

The *European Council Directive 1999/31/EC of 26 April 1999* on landfill sites requires EU countries to gradually reduce the amounts of biodegradable waste in landfill sites to, amongst other considerations, reduce their environmental impact. This target can only be achieved by segregating and recycling materials. By 2030, a maximum of 10% of the municipal waste may be deposited in landfills in the EU.

In Germany, the first federal ordinance regulating waste legislation was created in 1972 with the Waste Disposal Act. Today, the *Waste Management Act* (KrWG) is the core of waste legislation. The closed substance cycle of waste management is even more focused on resources, climate and environmental protection. The five-step waste hierarchy of the European Waste Framework Directive has been implemented. Based upon this, the waste management measure which is most appropriate to ensure the protection of the general public and the environment has to be chosen.

The implementation of the hierarchy in the steps of avoidance, recovery and disposal is already prescribed by law. The determination of the priority of a type of utilisation (reuse, recycling and recovery – including energy) is regulated with the defined heating value criterion of 11,000 kJ/kg (Sect. 8 para 3 KrWG).

So far, no specific regulation prescribes, so it is assumed that the energetic and material utilisation are equivalent if the calorific value of the segregated waste fractions is 11,000 kJ/kg. It is a presumption intended to prevent the use of energy from low-caloric waste, as its combustion does not provide a relevant contribution to resource conservation and thus cannot be regarded as a preferred environmental option.

In addition, recycling is promoted and secured by the introduction of the nationwide mandatory segregated collection for biowaste (Sect. 11 para. 1 KrWG), as well as for paper, metal, plastic and glass waste (Sect. 14 para 1 KrWG). By 2020, a recycling rate of at least 65% has to be reached for municipal waste (Sect. 14 KrWG). Further, there will be a general prohibition against mixing hazardous waste with other waste streams in the future (Sect. 9 para 2 KrWG). The separate collection of biowaste and recyclables is to make the high resource potential of this waste material more efficient.

After the ban on the landfilling of untreated municipal waste, the only possibility for reducing the annual emissions of climate-damaging gases in Germany is to increase the use of material and energy by increasing the efficiency of waste treatment plants and, in particular, by increasing the material recycling of waste streams [4].

2.2 Collection and Transport

Municipal waste in German households has been separated into different waste streams since the beginning of the 1990s. These separate waste streams are collected by citizens into waste disposal containers located at their residential buildings. This collection system is referred to as a kerbside system. It mainly collects paper and cardboard (blue bin), lightweight packaging (yellow bin/bag) and organic waste (usually brown bin). Reusable waste separated from households can also be collected at central collection points. This so-called bring system is mainly used for glass packaging (separated into green, brown and white glass) and old textiles. The collection at recycling centres and recycling points is also part of the bring system. There are different collection systems for bulky waste. Batteries and electrical appliances can be returned to the retailer, a special form of the bring system. The retailer also takes back returnable beverage containers.

Some of these collection systems are not uniform throughout Germany. However, in any event, a fraction of the municipal waste which is not recyclable remains the so-called residual waste.

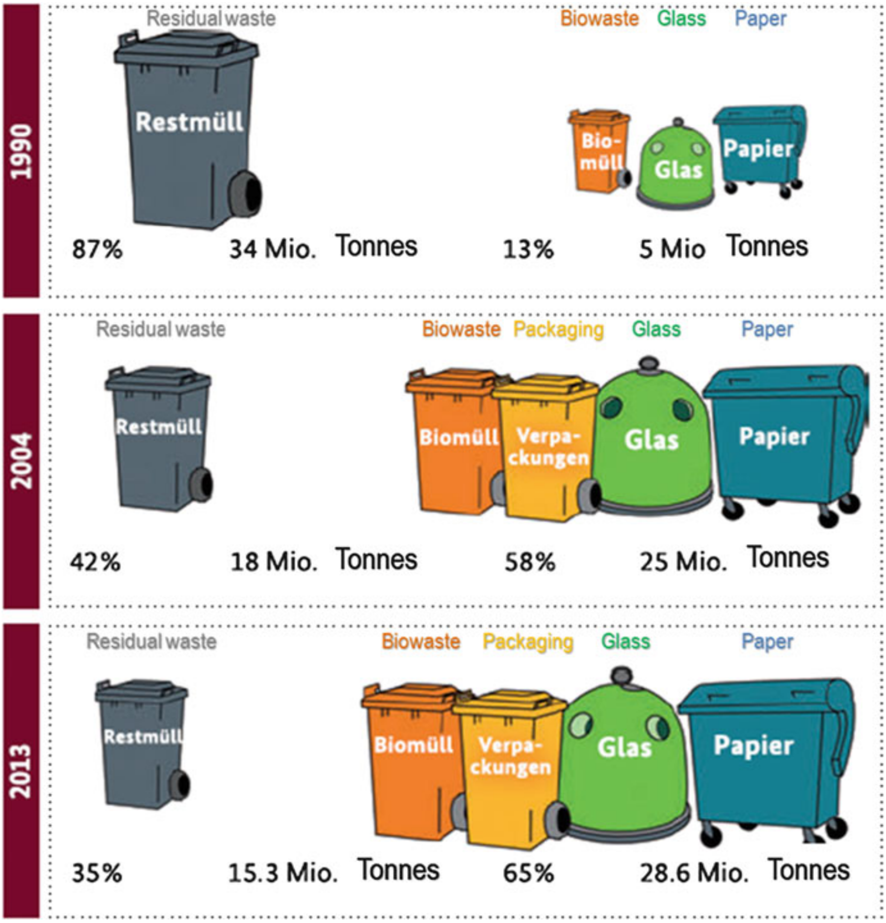

Fig. 5 Development of segregated collected amounts of different recyclables and residual waste in Germany (Source: [9])

Figure 5 shows the development of waste fraction segregation in Germany over time. While the amount of residual has decreased, the amounts of the different recyclable fractions (including biowaste) have increased. From 2004 on, the amount of recyclable materials collected separately was bigger than the amount of residual waste. Depending upon the need, there are different collection containers for the waste, ranging from plastic bags to bins (usually made of plastic) in different sizes. There are also many different models for the vehicles, which are mostly adapted to the household collection system [4].

On the basis of provisional data, as shown in Fig. 6, the Federal Statistical Office (Destatis) reports that a total of 37.3 million tons of waste were collected from households in 2015. This was a decline of 0.6% or 0.2 million tons compared with

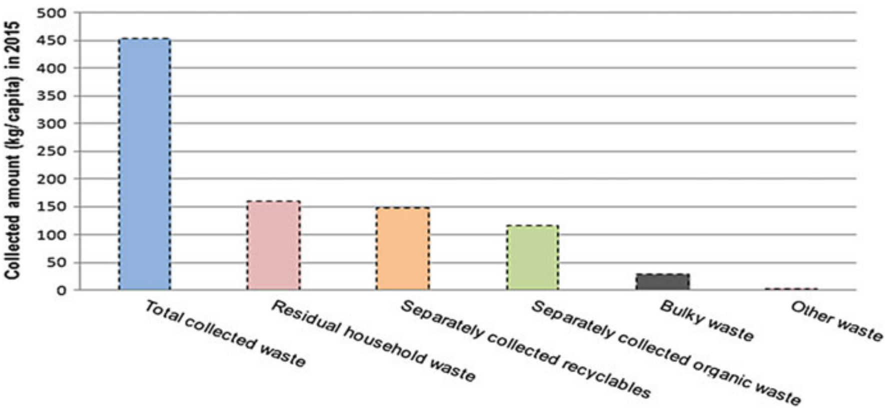

Fig. 6 Collected amounts from households (kg/capita) in 2015 (Source: [8])

2014. On average, roughly 454 kg of household waste were collected per inhabitant in 2015. Separately collected waste accounted for the major part (59%) of the total waste generated. It amounted to 21.9 million tons or 267 kg per head of the population [8].

2.3 German Concept for Waste Separation

In Germany, it is common to divide waste into different groups instead of throwing everything into the same bin. The reason is that separated garbage is reusable. Therefore, waste is not only separated in residential houses and dormitories, but also on the whole campus area and at other public places, such as the train station.

Various container systems and vehicles are used for waste collection and transport, depending upon the type of waste involved, whereby a distinction is made between systematic and systemless waste collection.

Systemless collection of household waste has, for the most part, given way to the use of a broad range of container systems whose main purpose is to allow for the source separation of various types of waste. The containers are placed either in very close proximity to households (pickup system), or at central locations (dropoff system). Residual waste is deposited into grey containers with the following different sizes: wheeled bins that can accommodate 120–140 L of waste, garbage bags and 1.1 m^3 containers that are used in settings such as large apartment buildings.

Information as to which types of waste can be deposited into which type of container is available from local authorities via waste collection schedules and the so-called waste ABCs, in printed form and/or online. Such waste collection procedures are governed by local waste ordinances, which stipulate waste collection charges, among other things.

Many different types of waste are collected in separate containers, which are a key precondition, especially for environmentally sound material recycling. This also allows for closed material cycles as far as possible, which makes a significant contribution to reducing primary raw material use [4].

In the 1990s, Germany established the so-called dual systems, which allows for separate collection recovery and disposal of *product packaging* in close proximity to households. Dual system use is governed by the Waste Management Act (Kreislaufwirtschaftsgesetz) and the Packaging Ordinance (Verpackungsverordnung). Table 2 provides the used transport and secondary packaging collected in 2014 [10].

Waste glass and paper are deposited into separate containers, located either in residential neighbourhoods, via depot containers, or at recycling yards. The latter facilities allow for the proper disposal of a broad range of recyclables and problematic wastes (hazardous waste). The Waste Management Act (Kreislaufwirtschaftsgesetz) calls for the separate collection of organic waste throughout Germany in the future (this is already done at the regional level).

The 2005 Electrical and Electronic Equipment Act (Elektro- und Elektronikgerätegesetz), stipulates that *electrical and electronic waste* is to be collected separately from unsorted municipal waste. This allows for the recovery of valuable secondary raw materials, such as metals, while also allowing for the proper disposal of pollutants.

Under German law, the 1998 Battery Ordinance (Batterieverordnung), subsequently superseded by the 2009 Battery Act (Batteriegesetz), *batteries* must be

Table 2 Used transport and secondary packaging collected in 2014[a] (Source: [10])

Type of packaging	Total quantity collected	Destination: Sorting facilities (in-house and external)	Destination: Recovery operators (including scrap merchants)
1,000 tons			
Packaging for the non-hazardous filling goods made of:			
Glass	114.9	80.0	35.0
Paper and cardboard	2,859.3	1,201.9	1,657.5
Metals	81.2	26.5	54.7
Ferrous metals	63.1	19.5	43.6
Aluminium	5.9	4.2	1.7
Other scrap metal, metal composites	12.2	2.8	9.4
Plastics	319.6	138.7	180.9
Wood	421.9	112.5	309.4
Composites	69.4	56.5	12.9
Other materials	481.0	270.2	210.8
Subtotal	4,347.4	1,886.3	2,461.1
Packaging for hazardous filling goods	8.5	1.7	6.8
Total	4,355.9	1,888.1	2,467.9

[a]Including sales packaging collected from commercial and industrial final consumers

collected separately and recovered. Retailers are required by law to take back waste batteries free of charge. For device waste batteries, this is done using collection containers, or via in-store collection points. German law also requires that scrap cars be drained, dismantled and recovered in an environmentally sound manner, so as to avoid direct environmental harm and allow for the recovery of recyclables.

These procedures are governed by the End-of-life Vehicles Ordinance (Altfahrzeugverordnung), which requires car producers to take back scrap cars free of charge via a comprehensive network. A vehicle owner wishing to dispose of their car is required to have this done via a recognised dismantling service or collection point.

Commercial waste generated by small businesses is likewise collected and transported via *household waste* containers (e.g. 240 L or 1.1 m^3 containers) or alternatively via exchange containers, which are also widely used for construction waste collection and transport.

Specific types of systems are used to collect and transport the various types of hazardous waste. For instance, garages collect waste oil in suitable containers, whereupon tank trucks transport the oil to waste oil recycling facilities. Below, an overview of the different waste bins is presented [11].

2.3.1 Black Bin

All non-recyclable waste such as leftover food, dirt, vacuum cleaner bags, cigarette butts, solid packaging, broken crockery, light bulbs, nappies and ashes are collected in the black bin.

2.3.2 Brown Bin

Organic waste, such as leftovers, fruit and vegetable waste, egg and nutshells, coffee filters, tea bags, as well as garden waste, like greenery and grass clippings, belongs in the brown bin/organic waste collection bin. For example, but not limited to, fluids, cigarette ends or diapers do not belong in this bin.

2.3.3 Blue Bin

Paper, newspaper, magazines, cardboard, leaflets, books and paper or cardboard packaging materials are collected in the blue bin.

2.3.4 Yellow Bin

Packaging such as empty tins, plastic packages, sheet, cans, aluminium packaging, beverage pasteboard containers and screw cap cartons (as these can be recycled) are collected in the yellow bin.

Furthermore, Fig. 7 below shows the collection system used for the different kinds of waste separated at the source in Germany.

Type of waste	Bins/container	Collection rhythms
Residual waste: All non-recyclable waste such as leftover food, dirt, vacuum cleaner bags, cigarette butts, solid packaging, broken crockery, light bulbs, nappies ashes, etc.	60–240 L  1,100 L 	5× per week to 1× per month
Organic waste: Leftovers, fruit and vegetable waste, egg- and nutshells, coffee filters, tea bags, as well as garden waste like greenery and grass clippings, belongs into the brown bin/organic waste collection bin. Fluids, cigarette ends, or diapers do not belong in this bin.	60–240 L 	1× per week to 2× per month
Paper waste: Into the so called blue bin, Paper, newspaper,, cardboard, leaflets, books, and paper or cardboard packaging materials and magazines.	60–240 L  1,100 L 	2× per month to 1× per month
Packaging material : Packaging such as empty tins, plastic packages, sheet, cans, aluminium packaging, beverage pasteboard containers and screw caps cartons as those can be recycled.	Sack  60–240 L  1,100 L 	2× per month to 1× per month

Fig. 7 Collection system used for waste separated at the source

2.4 German Environmental Awareness

A critical component in any waste management programme is public awareness and participation, in addition to appropriate legislation, strong technical support and adequate funding. Waste is the result of human activities, and everyone needs to have a proper understanding of waste management issues, without which the success of even the best conceived waste management plan becomes questionable [12].

One of the main causes of environmental degradation is improper management in the disposal of solid waste. It is a major cause of pollution and the outbreak of diseases in many parts of the world. There is no permanent solution for environmental problems; the only thing we can do to reduce and control waste generation is exercise proper awareness and practice [13]. Proper management of the waste generated is most important in this matter. Waste management is a science that addresses the logistics, environmental impact, social responsibility and cost of an organisation's waste disposal. Solid Waste Management (SWM) has three basic components, namely collection, transportation and disposal. Comprehensive solid waste management incorporates a diverse range of activities including reduction, recycling, segregation, modification, treatment and disposal, which have varying levels of sophistication [14].

In Germany, as shown in Table 3, greater public awareness of separation, reuse and recycling avenues is achieved through a number of good practice measures, such as the use of media, holding awareness workshops, distribution of brochures and circulating the idea in the universities, schools and kindergartens [15].

The environmental awareness of Germans remains at a high level: 91% of the population rates environmental protection as important, according to the results of a new study on environmental awareness in Germany, which was commissioned by the German Federal Environment Ministry and the Federal Environment Agency (UBA). The study also points out that consciousness of the risks and consequences of global warming is very high. Over 80% of respondents are apprehensive about the high costs that Germany will incur to repair damage or for protection against the consequences of climate change. At the same time, the number of people who believe the effects of climate change in Germany are manageable rose from 39% in 2006 to 54% now.

From the waste separation point of view, the German system of waste separation was deemed by many as slightly absurd; it did create a commercially profitable recycling industry. In the face of growing commodity shortages, the recycling of paper, glass, metal and plastic waste is an increasingly important economic factor. According to the Federation of the German Waste Management Industry, Germany saves nearly 4 billion euros a year in commodity and energy costs by 'urban mining', i.e. the extraction and supply of secondary raw materials. Figure 8 shows an example of the public awareness of separation via separation posters adopted in Rostock as part of the deployment of the environmental awareness policy among the citizens [16].

Table 3 Measures used in Germany for raising public awareness of various waste management issues

Measures	Activities
Disseminating waste separation messages through the printed media (awareness posters)	Disseminating awareness posters to spread green messages as reminders that encourage behavioural change as well as to create awareness for all of environmental awareness plans/goals (separation, recycling, etc.)
Disseminating waste separation messages through the printed media (awareness decals)	Spreading awareness decals or stickers on or near a machine, a doorway, etc. to send an environmental awareness message as a reminder regarding waste separation, recycling, environment protection, etc.
Disseminating photos and banners	Disseminating photos and banners in a road show promoting the programme on source separation of domestic waste
Local media	– General awareness promoting through the local media, including television, radio stations and local newspapers. Producing television programmes, explaining the waste problem and showing how to practise waste separation at home. Also, announcements of public interest on a variety of waste issues – Spread green messages through the mass media and community outreach programmes
Working with schools	– Organising education programmes targeting schools with a focus on waste management problems – Engaging schools in waste management efforts (reduction, separation, recycling, etc.) – Equipping secondary schools with recycling bins and placing demonstration bins in preschools – Organising workshops and trainings featuring waste reduction for schools to increase awareness among young people
Working with community organisations	Implement publicity programmes to promote community participation in waste management issues and build the capacity of less experienced groups in promoting and organising environmental activities
Handouts and giveaways	Inclusion of messages related to environmental issues in handouts and giveaways in terms of environment protection, waste separation, waste recycling, etc.

There is a lot of confidence placed in technological innovation as a solution to the problem. Some three-quarters of respondents expect increased economic competitiveness as a result of an ambitious environmental protection policy.

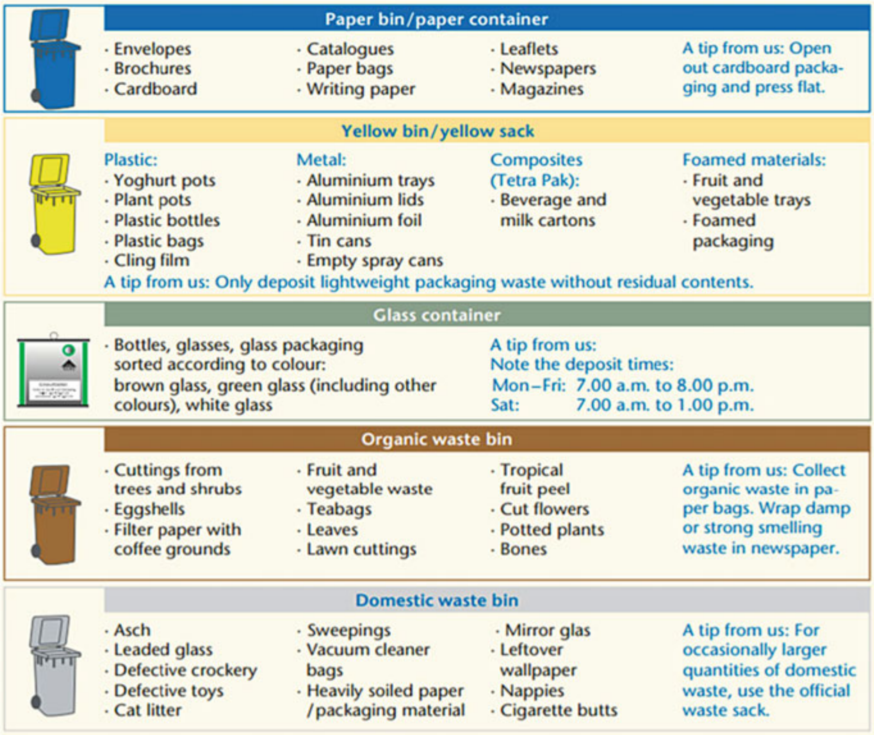

Fig. 8 Waste separation in Rostock (Source: [16])

Nevertheless, the public does not simply dismiss its personal responsibility: a large majority agree with the statement that we must all change our everyday habits.

References

1. Statistisches Bundesamtumwelt (2014) Federal Statistical Office environment. https://www.destatis.de/EN/FactsFigures/NationalEconomyEnvironment/Environment/EnvironmentalSurveys/WasteManagement/Tables/TablesWasteBalanceOverview.html. Accessed 5 Jan 2017
2. Jaron A, Flaschentreher N (2012) Waste management in Germany 2013. German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), Berlin
3. Schüch A, Morscheck G, Lemke A, Nelles M (2016) Bio-waste recycling in Germany – further challenges. Proceedings of international conference on solid waste management, 5IconSWM 2015. Proc Environ Sci 35:308–318
4. Nelles M, Nassour A, Elnaas A, Lemke A (2017) Recycling and recovery of the biogenic fraction from municipal solid waste in the PR of China. Study by University of Rostock
5. Nelles M, Grünes J, Morscheck G (2016) Waste management in Germany – development to a sustainable circular economy? Proceedings of international conference on solid waste management, 5IconSWM 2015. Proc Environ Sci 35:6–14

6. Bilitewski B, Härdtle G (2013) Abfallwirtschaft. Handbuch für Praxis und Lehre 4 (Waste management. Manual for practice and theory 4). Aktualisierte und erweiterte Auflage. Springer, Berlin Heidelberg 1990, 1993, 2000, 2013. ISBN:978-3-540-79530-8
7. UBA (2010) Klimaschutzpotenziale der Abfallwirtschaft; Umweltbundesamt (Climate protection potentials of waste management; Environmental Protection Agency). UBA Text 06/2010. https://www.ifeu.de/abfallwirtschaft/pdf/Klimaschutzpotential_Endbericht%20UBA-Texte%2006-2010.pdf. Accessed 20 Dec 2016
8. Statistisches Bundesamtumwelt (2015) Federal Statistical Office environment. Statistisches Bundesamt Text 12/2016. https://www.destatis.de/EN/PressServices/Press/pr/2016/12/PE16_465_321.html. Accessed 5 Jan 2017
9. BMUB (2015) Bundesministerium für Umwelt. Federal Ministry for the Environment. http://www.bmub.bund.de/fileadmin/Daten_BMU/Pools/Broschueren/abfallwirtschaft_2016.pdf. Retrieved Aug 2016; Accessed 12 Oct 2016
10. Statistisches Bundesamtumwelt (2014) Federal Statistical Office environment. https://www.destatis.de/EN/FactsFigures/NationalEconomyEnvironment/Environment/EnvironmentalSurveys/WasteManagement/Tables/TransportSecondaryPackagingCollected.html. Accessed 4 Jan 2017
11. UBA (2014) Waste collection and transport. Umweltbundesamt, UBA Text 01. https://www.umweltbundesamt.de/en/topics/waste-resources/waste-disposal/waste-collection-transport. Accessed 3 Jan 2017
12. Hasan S (2004) Public awareness is key to successful waste management. J Environ Sci Health A39:483–492
13. Licy CD, Vivek R, Saritha K, Anies TK, Josphina CT (2013) Awareness, attitude and practice of school students towards household waste management. J Environ 2(6):147–150
14. Zagozewski R, Judd-Henry I, Nilson S, Bharadwaj L (2011) Perspectives of past and present waste disposal practices: a community based participatory research project in three Saskatchewan First Nations Communities. J Environ Health Insights 5:9–20
15. UBA (2008) Environmental awareness among Germans is high. Umweltbundesamt, UBA Text 12. https://www.umweltbundesamt.de/en/press/pressinformation/environmental-awareness-among-germans-is-high. Accessed 4 Jan 2017
16. Hansestadt Rostock (2011) Municipality of Rostock. http://rathaus.rostock.de/sixcms/media.php/144/Abfallratgeber%20englisch.59502.pdf. Accessed 6 Jan 2017

Separation of Municipal Solid Waste in Treatment Plants

Daniel Schingnitz

Abstract The sustainable management of waste has attained increasing importance due to the rising total amounts of waste, as well as the high diversity of the waste fractions worldwide. Increased urbanization rates are resulting in changes in the economy and demography. The suitable management of generated waste streams and using the high potential of recyclables inside these waste streams are major topics communities have to deal with. Especially in Asian countries, the fast development of the society and the rising amounts of waste is resulting in significant problems in sustainable waste management. As the largest emerging country with the largest population in the world, China faces different waste treatment situations than other developing countries. Several technologies can be used for waste treatment depending on the amounts and compositions of the waste streams. Recycling processes should be used for material recovery, biological treatments for appropriate streams, as well as thermal treatments for energy recovery. Landfills for the disposal of residues generated by the other treatments are also necessary. In the challenge of avoiding the presence of biodegradable waste in landfills and increasing recycling, mechanical biological treatment (MBT) plants have seen a significant increase in number and capacity in the last two decades in Europe. Among the conditions and local challenges in countries in Asia, which are at the beginning in implementing a regulated waste management system, MBT technologies can be a promising approach.

Keywords Mechanical biological treatment, Municipal solid waste, Refuse-derived fuel, Waste composition, Waste management

---

D. Schingnitz (✉)
Institute of Waste Management and Circular Economy, Technische Universität Dresden, Dresden, Germany
e-mail: daniel.schingnitz@tu-dresden.de

R. Maletz et al. (eds.), *Source Separation and Recycling*,
Hdb Env Chem (2018) 63: 89–104, DOI 10.1007/698_2017_27,
© Springer International Publishing AG 2017, Published online: 28 April 2017

Contents

1 Introduction

The sustainable management of waste has attained increasing importance worldwide. The Asian continent is a huge and diverse region. The economy and demography on the continent have been accompanied by increased urbanization rates. High urbanization rates have been pushing the boundaries of cities. Among these, the increasing quantities of generated municipal solid waste (MSW) is one of the significant challenges city governments have been facing. In China, more than 300 million tons of MSW are generated annually, compared with approximately 45 million tons of MSW in Germany each year [1, 2]. The management of MSW encompasses a multidimensional set of activities where different actors, processes, and policies converge and interact. In developing Asian countries, waste separation rates are typically low. This can be ascribed to a number of factors, such as the low awareness of populations of the benefits and need to segregate waste, and the low willingness to comply with segregation practices due to a lack of incentives or penalties. Hence, the utilization of MSW as an energy resource is stirring interest among public authorities around the world, and especially in China. Nevertheless, the Chinese government faces great difficulties in providing MSW management services in rural China.

Several technological means exist to divert solid waste typically destined for a landfill, such as incineration, the composting of organic wastes, and material recovery through recycling. All have the potential to be more sustainable methods than landfilling. Reuse and recycling are aimed at pursuing effective material recovery. For those streams of waste, for which the material recovery is not effectively applicable, energy recovery is the path to be followed. The thermal treatment of waste is an indispensable part of every integrated waste management system. Thus, an integrated waste management system should be designed that integrates the different types of treatment processes: recycling processes for material recovery and biological treatments for appropriate streams, as well as thermal treatments for energy recovery, should be provided with serviced landfills for the disposal of residues generated by the other treatments (see Fig. 1). The transition from waste treatment and landfill dependency to sustainable resource management includes the production of safe, environmentally sound, and marketable outputs. Besides direct combustion (waste incineration) or the biological conversion of organic matter into biogas and/or compost, the energy content of waste can be utilized by producing solid fuels. These secondary fuels can be used in power plants and cement kilns (co-combustion) or in mono-combustion plants. Refuse-

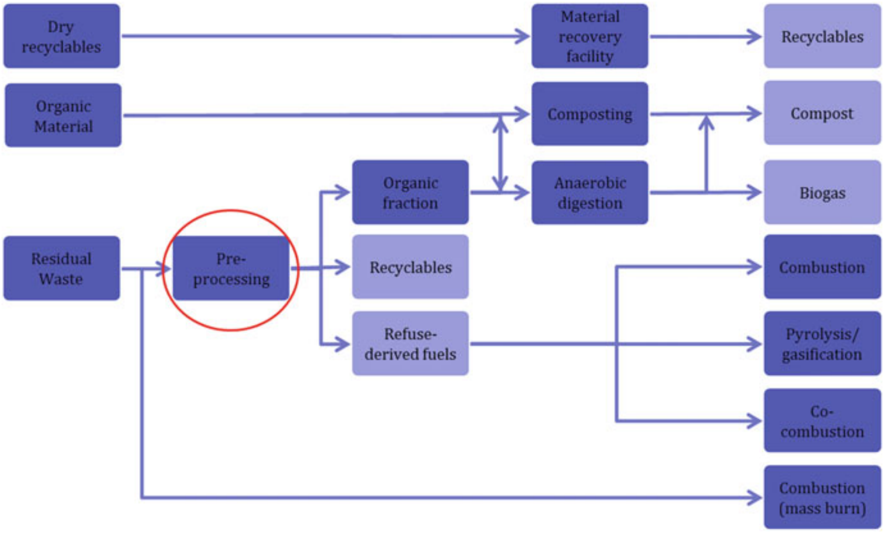

Fig. 1 Treatment options for Municipal Solid Waste (MSW)

derived fuel (RDF) is defined differently across countries: it usually refers to the separated, high calorific fraction of MSW, commercial or industrial wastes.

Learning from the experience of the first market failure of RDF in Europe, today the quality of the fuel is receiving significant attention during the production process in order to fulfill market requirements. As landfill taxes in many European countries have risen, as well as the impending Landfill Directive, the market for mechanical biological treatment (MBT) plants has seen significant growth. According to a recent report, between 2005 and 2011, the number of operational MBT facilities in Europe rose by almost 60% to a total of 330 [3]. MBT, which is characterized by the implementation of material-specific treatment, can be combined with energy recovery and/or material recycling and represents a valid and often preferential alternative to conventional thermal waste-to-energy (WtE) plants. Exemplarily, approximately four million tons of RDF from 39 MBT plants were produced in Germany in 2010 [4]. The excessive supply of secondary fuel and the possibility of earning money led to an increased interest in RDF-fired boilers for the mono-incineration of RDF. In 2012, 36 RDF-fired combustion plants existed in Germany with a total capacity in the range of 4.8–5.4 million tons [5, 6]. Nowadays, in Germany different treatment methods for the production of RDF are used, depending on the origin and composition of the waste (see Fig. 2), although more than 60% of the residual waste is still burned directly in WtE plants. In choosing MBT techniques, characteristics like a high organic content of the waste require the combination of mechanical treatment steps, as well as drying processes of the waste or the degradation of the organic content by composting or digestion. The developing national as well as European market for RDF requires standardized quality-assured measurement methods to improve the chances for marketing and to assure environmental standards. The production of RDF from different

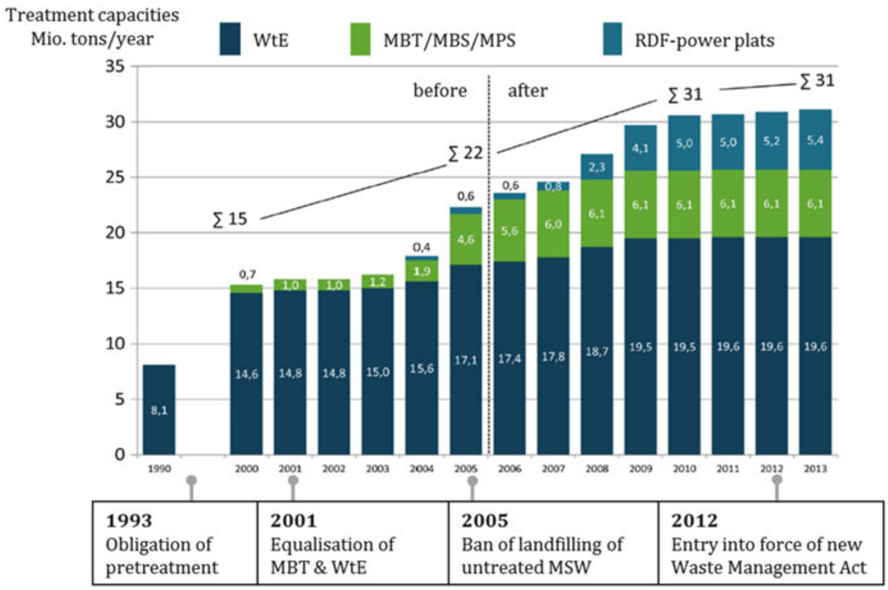

Fig. 2 Treatment techniques for residual waste in Germany [5]

types of waste and their thermal utilization in co-incineration and mono-incineration plants can be useful alternatives with regard to the substitution of fossil fuels. However, the heterogeneous properties of the RDF are problematic during the intended utilization processes. Regular quality controls are required during the treatment and utilization processes.

2 Waste Characteristics and Future Tendencies for Municipal Solid Waste

Considering the management of MSW in developing countries, attention needs to be paid to the characteristics and properties of the waste that is generated, as well as the specific amounts. These include aspects such as the quantities of waste generated, waste composition, density, moisture content, and calorific value. Waste characteristics can differ significantly among developing and developed countries. Comparing the compositions of residual waste in Germany and MSW in China, relevant differences in the content of organics as well as fine fractions are apparent (see Figs. 3 and 4). In Germany, a high concentration of recyclables (e.g., plastics, glass, paper and cardboard, metals) is collected separately. This also influences the composition of the leftover residual wastes. The usual content of organic materials in German residual waste differs between 20 and 40 wt.-%. Of course, the portion of recyclables in residual waste streams is lower than without separate collection systems.

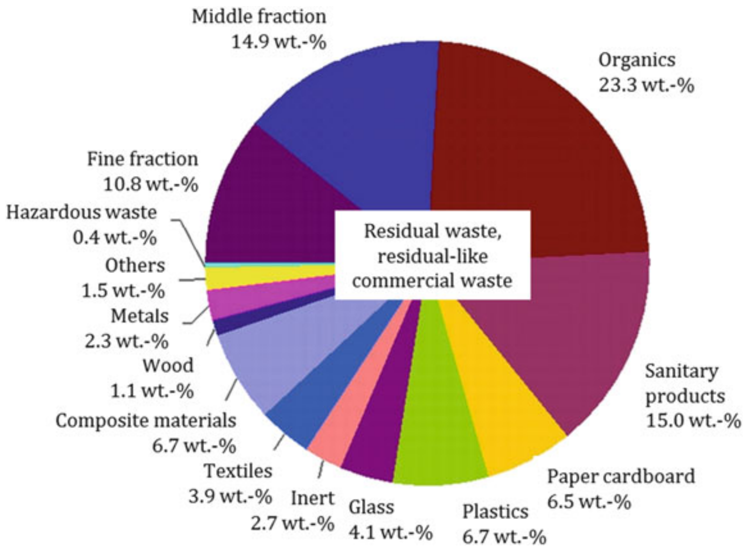

Fig. 3 Typical composition of residual waste in Germany in 2012 [1, 7]

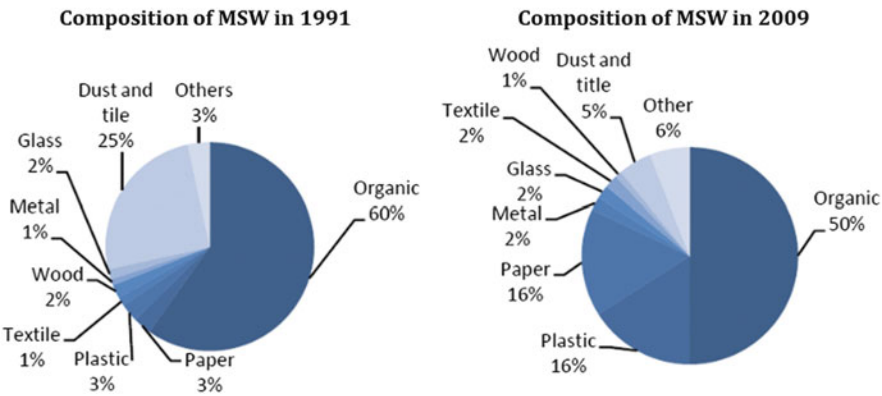

Fig. 4 Typical composition and trends of MSW in China [2]

While comparing the composition of MSW in China between 1991 and 2009, changes in the composition of the MSW can be identified. Due to the changing consumption behavior of the people and the economic growth of the country, the rising content of recyclables, as well as declining ratios of organics is evident in the composition of MSW. The higher concentration of recyclables in generated waste streams can facilitate an efficient mechanical pretreatment of the waste for a sustainable material recovery of recyclables. A separate collection of recyclables in MSW in China is only partly implemented in the major cities. However, in developing countries, the moisture content of waste is 50 wt.-% or higher, while in developed countries it is usually in the range of 20–30% wt.-% [8]. Furthermore, waste that is rich in organics and moisture can also impair the value of (inorganic) recyclables that can be recovered from waste.

Several technologies and methods for treating and processing MSW are also available in developing countries. The prior objective is always to reduce the volume of waste and/or divert waste streams from disposal sites and the natural environment, which are the source of negative externalities. The treatment of waste also offers the potential for recovering resources from discarded materials, either in the form of energy, recycled materials, or soil fertilizer.

In China, uncontrolled landfilling of MSW is still the most common means of waste removal in rural areas. Cities with a high population density, representative of nearly all urban regions in China, start to focus on thermal waste treatment technologies, as well as in some cases also composting techniques for waste fractions with high organic concentrations (see Fig. 5). By using the example of the city of Shanghai, the installed waste treatment techniques illustrate a rising share of incineration and composting of MSW, as well as lower percentages of landfilled and dumped MSW. Nowadays, incineration is one of the waste treatment options endorsed by both national and local governments. In 2010, there were around 160 incinerator plants in operation [12]. Over 560 treatment plants are running to treat approximately 50% of the generated MSW in China, and more than 450 landfill sites are still in operation [2]. MBT is infrequently applied in developing Asian countries. These are typically capital intensive plants with high upfront and maintenance costs, often deployed alongside material recovery facilities compared with landfill or dumping sites. Material recovery of MSW in Asia is mainly realized through informal sector activities. Usually, informal waste sector activities are driven by the need to eke out a living rather than environmental concerns. For the urban regions in China, informal recycling rates were estimated in the range of 17%–38% [13]. By implementing new MBT techniques for Chinese MSW, the amount of recyclables that can be generated from the waste streams can be increased. Also, high organic concentrations causing high water content in the MSW can be treated.

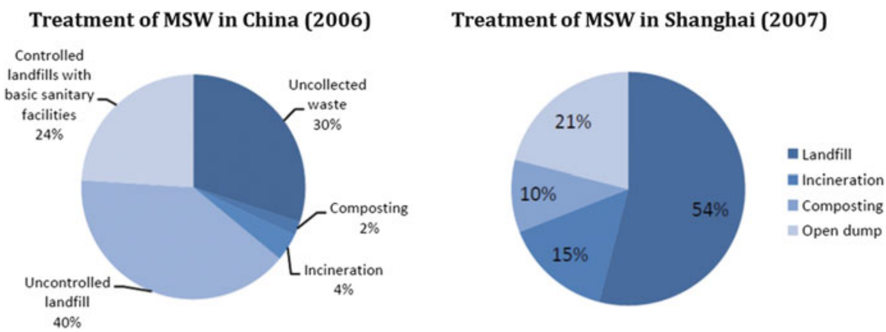

Fig. 5 Treatment techniques for MSW in China [2, 9–11]

3 Mechanical Biological Treatment Techniques for Municipal Solid Waste

Between different fractions, the organic part presents the major component of MSW in developing countries. Because of its biodegradation in landfills under anaerobic conditions, this is the major fraction affecting waste pollution in landfills. The reduction in the organic fraction of MSW to be landfilled can be obtained by three different approaches: (1) source-separated collection of organic fraction of MSW to produce compost; (2) MSW burning using WtE techniques to produce energy, and (3) MBT of MSW to produce a stabilized or a compost-like material prior to landfilling. Also, the original purpose of MBT plants – as they were in operation in Europe during the 1990s – was to divert from landfills disposable biodegradable substances that are associated with the main polluting emissions (landfill gas and leachate). As a consequence, the long-term pollution potential of landfills can be decreased significantly in the overall purpose of protecting the environment and human health. MBT plants have some basic principles in common: they generally integrate mechanical processing with a bioconversion step. The waste is mechanically pretreated in order to prepare it for subsequent biological processing. Besides homogenization and shredding, this may include the separation of metal fraction (ferrous and nonferrous) for material recycling or a high calorific fraction for energy recovery. The biological treatment consists of either aerobic degradation (rotting and composting) to reduce the share of biodegradable substances and produce a stabilized material for environmentally sound landfilling or biological drying. This produces RDF for energy recovery and provides an option for advanced material recovery (metals and plastics) from the dried waste output by mechanical posttreatment. Or finally, a combination of anaerobic digestion (fermentation) for biogas production and aerobic stabilization prior to the final disposal of the residual fraction.

Comparing all possible MBT processes for MSW, the processes are usually divided into two basic principles (see Fig. 6). The major difference in these two basic principles is the order of mechanical and biological treatment steps. The processes can be used for the treatment of MSW and/or residual wastes.

On the one side, separation processes using mechanical and biological treatment steps always start with a mechanical sorting of the waste stream by using separation technologies (magnets, eddy current separator, and near-infrared detectors) as well as classifying technologies (sieves) for material recovery. Also, the separation of the fine fractions for the following biological treatment step is done using sieving processes. Fractions with larger grain sizes usually include higher concentrations of recyclables and are therefore more suitable for mechanical sorting steps. The downstream biological treatment can be done for fine fractions with high organic contents by using aerobic treatment steps (rotting and composting) or anaerobic processes (digestion). By using digestion processes, biogas is produced, which can be used for heat and electricity production. The length of the biological treatment can vary so that biostabilized products show different degrees of biological stability. Finally, organic

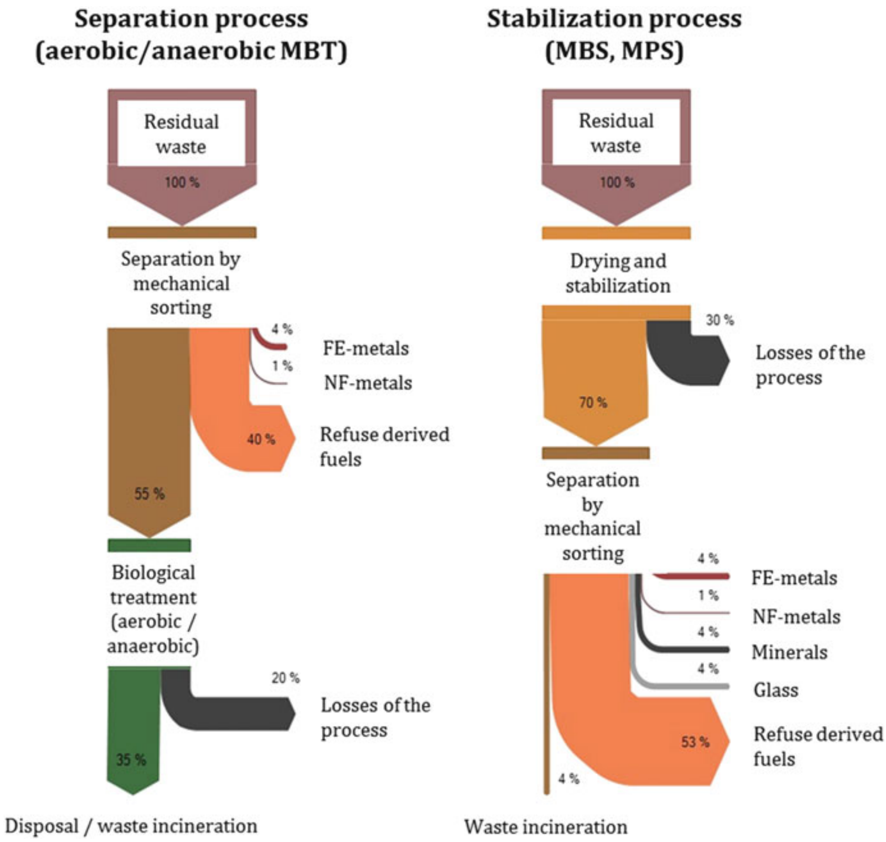

Fig. 6 Basic principles of Mechanical Biological Treatment (MBT) processes for MSW [14, 15]

concentrations can be minimized, and in the case of digestion biogas can be produced for energy recovery.

On the other side, stabilization processes can be used for MSW treatment as a second basic principle. Therefore, the waste stream is treated biologically by using drying or stabilization techniques as a first step. The aim of this stabilization is reducing the water content and the concentration of organic materials. Common techniques for the stabilization of MSW are biological and physical treatment. Biological stabilization processes operate by using the effect of self-heating the waste due to the activities of microorganisms, which decompose the organic material. The generated heat leads to drying, and the microorganism reduces the organic content of the waste. Using physical stabilization processes also ends up reducing the water content of the waste. Therefore, additional energy – usually fossil fuel – is necessary. Accordingly, physical stabilization causes higher treatment costs than biological stabilization but can result in less water content. The need for fossil fuel as an auxiliary fuel is the major reason that the processes of physical stabilization of MSW are not widespread in Germany and Europe. After the stabilization of the

MSW, the separation of recyclables and valuables is done by using mechanical sorting processes.

Both treatment process principles generate fractions of recyclables and RDF, as well as always a final fraction for landfilling or WtE processes as a residue. The ratio of recyclables and RDF depends significantly on the composition of the generated MSW. The aim of removing recyclables from the waste stream is to separate materials that have enough value to make their recovery worthwhile. The shredded and in some cases pelletized fraction of combustibles such as RDF can be used in mono- or co-incineration plants. Using MBT techniques in Germany, it is possible to generate RDF in different qualities of approximately 50 wt.-% of the input material by stabilization processes and approximately 40–45 wt.-% by using separation techniques [14, 15].

4 Mass Balances for Mechanical Biological Treatment

On the basis of German circumstances, the following figures show the mass balances of MBT processes including anaerobic digestion (see Fig. 7), as well as biological stabilization processes of residual waste (see Fig. 8). As already mentioned, using the principle of separation processes, it is possible to recycle 1–2 wt.-% of metals, 40–45 wt.-% of RDF for downstream mono- or co-combustion processes, as well as approximately 8–10 wt.-% of biogas for combined heat and power generation. The separation process of residual waste generates lower amounts of RDF with higher qualities compared with stabilization techniques like those in Fig. 6. RDF, which is sorted using mechanical treatment techniques in a first step, does not include high concentrations of organic materials. Usually, fractions with high calorific values like plastics, composite materials, wood, textiles as well as paper and cardboard are separated. Besides the high calorific values, these fractions are characterized by lower chlorine concentrations, little water and ash content, and nearly no biological activities.

The RDF produced is preferably used for co-combustion in cement kilns. Plastics made out of polyvinylchloride have to be removed from the RDF stream because of their significantly higher chlorine concentrations, which can cause corrosion processes while combusting.

Using biological stabilization processes, it is possible to generate up to 50 wt.-% of RDF as well as ferrous and nonferrous metals in a similar range by using separation processes. There is no additional option for energy production from the waste stream by producing biogas. The higher amounts of RDF separated are characterized by lower quality because of the higher contents of organic materials. This results in lower calorific values and in some cases higher chlorine concentrations. So, the RDF for stabilization processes seems to be more suitable for usage in (brown)coal-fired power plants and mono-incinerators for RDF.

Comparing all different kinds of MBT processes for residual waste in Germany, it is obvious that in total, half of the residual waste is used as RDF and only less

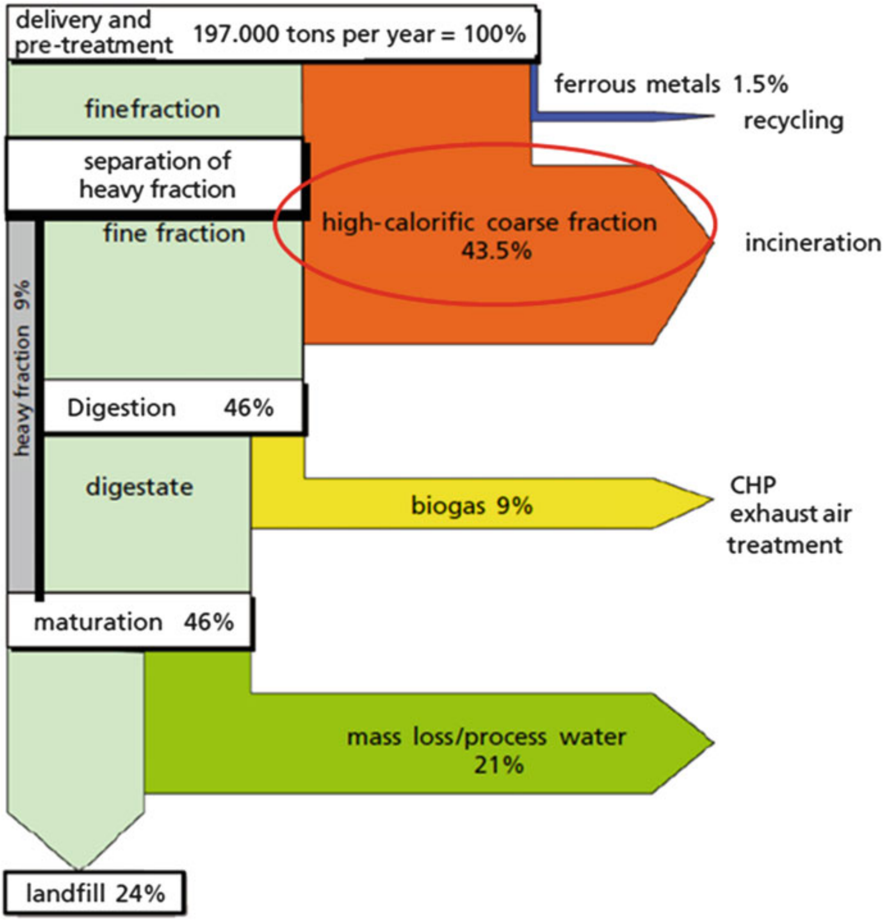

Fig. 7 Mass balance of anaerobic MBT process of residual waste in Germany [4]

contents are used for material recovery and biogas production (see Fig. 9). In Germany, only 5 wt.-% of the treated residual waste is sorted out by MBT for material recovery. Major components for material recovery are ferrous metals because of their concentration inside the waste streams, as well as the easy method of sorting by magnets. Also, relevant amounts of fractions like nonferrous metals and inerts are removed for material recovery. Ferrous and nonferrous metals are recycled into new steel and metal products. Inert materials can be used for road or landfill construction. Also, removed batteries can again be added to the process of battery recycling. Fractions like textiles as well as paper and cardboard collected comingled with the other fractions of the residual waste are not suitable for material recovery processes due to the high amount of impurities. Also, composite materials are difficult to use for material recovery because of their high heterogeneity and the need for complex separation steps by mechanical systems for the single materials. In both cases, processes for

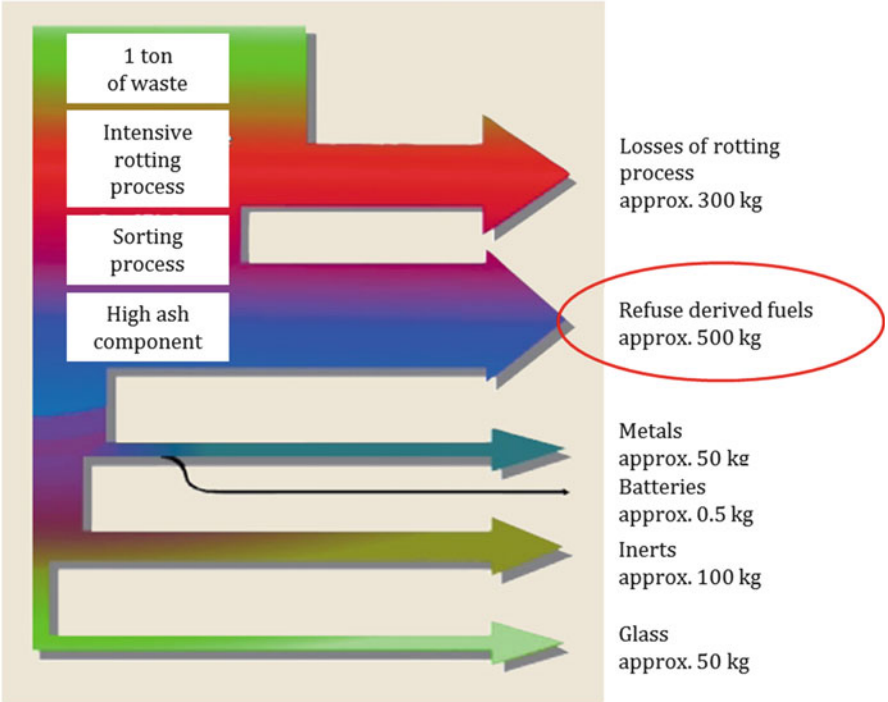

Fig. 8 Mass balance of aerobic Mechanical Biological Stabilization process of residual waste in Germany [16]

energy recovery (WtE) seem to be suitable and metals contained can be removed from the generated slag.

The German mass balance for MBT processes is influenced by a lot of factors. First of all, the practiced segregation at the source influences the composition of the leftover residual waste. By the separate collection of recyclables and in some cases also of biowastes, MBT techniques reach fewer ratios in the case of material recovery and biogas production.

Currently in Germany, the RDF produced from residual waste is mainly used in mono-incineration plants for electricity, heat, and/or steam production. Approximately 36 RDF power plants combusted 4.8 million tons of RDF by using grate firing or fluidized bed incineration systems [6]. The co-incineration of RDF in coal-fired power plants as well as cement industries for the substitution of fossil fuels (coal, gas, and oil) is realized in approximately 40 German plants by using 2.3 million tons of RDF [6]. The requirements for RDF utilization in different mono- or co-combustion plants differ. Cement kilns make high demands on the quality of the produced RDF, especially for calorific value, chlorine content, and water content. Mono-incineration plants can handle RDF with less quality and without major problems. Figure 10 illustrates an overview of the usage of high calorific fractions from

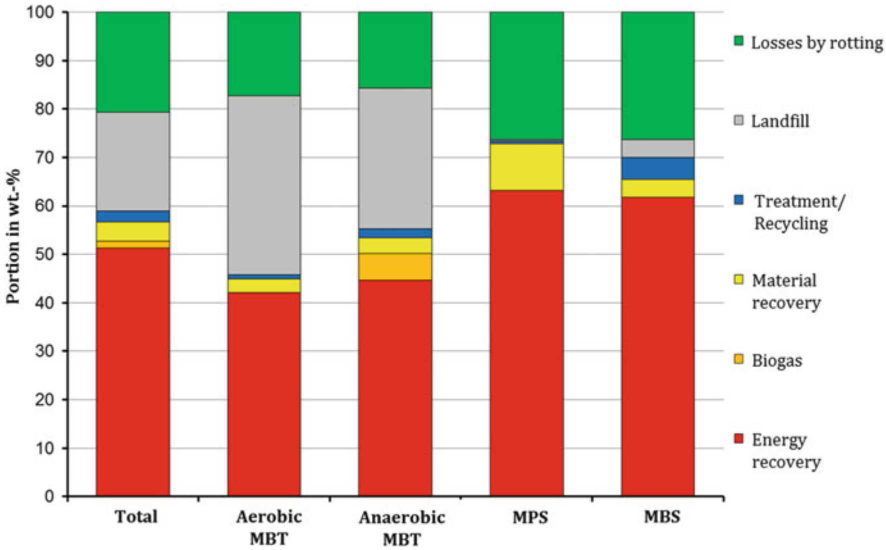

Fig. 9 Mass balance of MBT processes in Germany in 2011 [4]

waste in incineration plants in Germany over the last 20 years. Therefore, the rising amounts of used RDF in mono-incinerators can be analyzed.

For developing countries, the specific amount of recyclables compared with the input material of the MBT process can be even higher due to the missing separation of recyclables at source. Also, a more significant reduction in organic contents can be reached by using MBT processes because of the higher concentrations of bio-wastes in MSW. The treatment of MSW with separation or stabilization processes can improve the characteristics for downstream WtE processes, as well as increase the amount of material recovery of MSW. Common thermal incineration technologies are technically and economically challenging because of the lower calorific value of waste streams that are rich in organics and moisture. Specific approaches and methods are therefore required for designing adequate waste management systems in China. Therefore, MBT techniques can be one example of suitable pre-treatment of MSW before landfilling or incineration.

Sustainable material recovery from MSW always involves the demand on recyclables as well as the suitable recycling processes. Also, the generation of RDF in developing countries requires power plants that are going to use the RDF produced. If power plants are still using fossil fuels at cheap prices, there will be no market for RDF, and the expenditures of MBT for the MSW generated will be higher than the economic benefits. Also, the material recovery of plastics will generate no significant economic advantage in the case of low prices for fossil fuels. In addition, despite the common characteristics shared among cities in developing countries, their specific circumstances can vary significantly, especially within a big country like China, calling for the need for framework-specific waste management approaches.

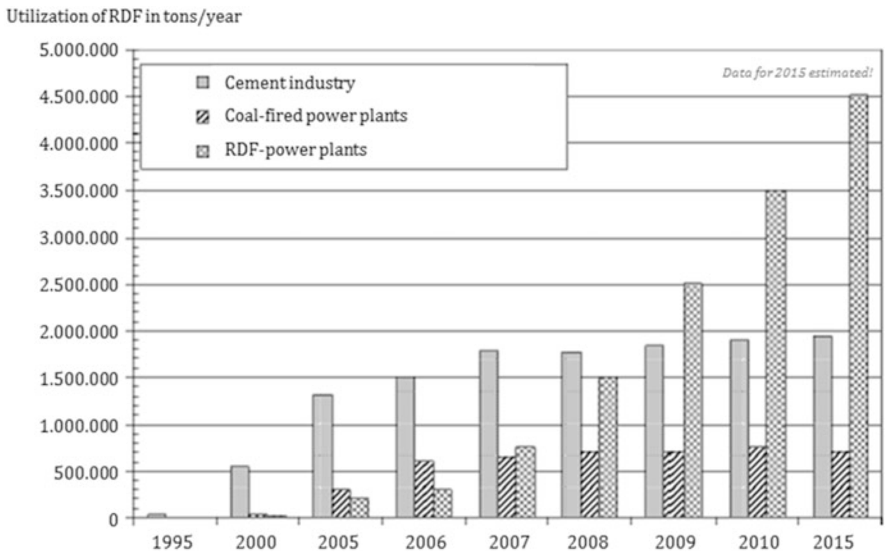

Fig. 10 Utilization of Refuse-Derived Fuels in Germany [17]

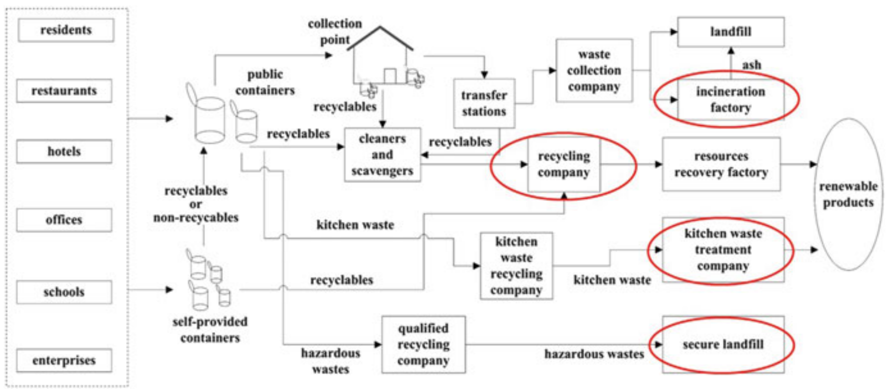

Fig. 11 Waste Management concept for developing countries [18]

5 Conclusions

The rapid urbanization progress and the continuous improvement of rural residents' living standard contribute to the increase in MSW in China. As the largest emerging country with the highest population in the world, China faces different situations for MSW treatment than other developing countries. Meanwhile, the method of source-separated collection of MSW in rural areas is different from urban areas in China. Worldwide experience shows that the source-separated collection of MSW is an effective method for the enhancement of waste reduction and recycling. The separation of waste significantly influences the amount and value of the resources that can be recovered from the different MSW streams, and therefore it is the backbone of any approach in the reuse and recycling of waste. The separation of waste at the source is a participatory measure that requires the cooperation of those who generate waste, such as individuals, households, or commercial establishments. In the challenge of avoiding the presence of biodegradable waste in landfills and increasing recycling, MBT plants have seen a significant increase in number and capacity in the last two decades in Europe. The aim of these plants is separating and stabilizing the quickly biodegradable fraction of the waste, the production of RDF as a substitute fuel for energy recovery, as well as recovering recyclables from mixed waste streams. In addition, the mechanical treatments performed in MBT plants allow for the recovery of valuable materials such as iron and aluminum. Also, the content of organics can be reduced by composting or the digestion of organic materials. Minimizing the biological activity of waste streams benefits in fewer emissions while landfilling (leachate and landfill gas). By raising the fuel-relevant parameters (e.g., content of combustibles and heating value), it can also improve the usage of the MSW for common thermal processes (WtE). The waste composition principally affects the magnitude of the benefits associated with recycling. One of the advantages of using MBT techniques is the flexible system, which is viable with small flow rates as well as larger flow rates of the waste and – compared with incineration plants – lower investment costs. Among the conditions and local challenges in countries which are at the beginning of implementing a regulated waste management system, MBT technologies can be a promising approach. Finally, a suitable MSW management system includes several steps for waste collection, separation, and treatment, as well as the final disposal, depending on the waste streams and the characteristics of these waste fractions (see Fig. 11).

References

1. Statistisches Bundesamt (2015) Haushaltsabfälle (ohne Elektrogeräte) 2014 (residual wastes (without electric devices) 2014). Germany, Published https://www.destatis.de/DE/ZahlenFakten/GesamtwirtschaftUmwelt/Umwelt/UmweltstatistischeErhebungen/Abfallwirtschaft/Abfallwirtschaft.html
2. Yang C (2011) Municipal solid waste management in an urban area of China: case studies of Shanghai, China and Linköping, Sweden. Linköping University, Sweden. Master's Thesis, ISRN: LIU-TEMAV/MPSSD-A--12/007--SE
3. Messenger B (2013) Where next: for the European waste derived duels marked? In: Waste management world. INDUSTRIEMAGAZIN Verlag GmbH, Austria. Published https://waste-management-world.com/a/where-next-for-the-european-waste-derived-fuels-market
4. Balhar M, Vielhaber B (2015) Zukunft der MBA bei vermindertem Bioabfallanteil – Chancen für Abfallbiogasanlagen (Future of MBT in case of reduced contents of biowastes – chances of biogas production from waste). Eigenverlag des Forums für Abfallwirtschaft und Altlasten e.V., Pirna, Germany, pp 49–54. ISBN 978-3-934253-90-2
5. Prognos (2014) Analyse der Situation der Vorbehandlungskapazitäten in Deutschland und Thesen für eine Abfallwirtschaft im Gleichgewicht (Analysis of the situation of pre-treatment capacities in Germany and theses for a waste management in balance). Green Paper, Prognos AG, Berlin, Germany

6. Thiel S (2013) Ersatzbrennstoff-Kraftwerke in Deutschland und Österreich (RDF power plants in Germany and Austria). In: Energie aus Abfall. TK Verlag Karl Thomé-Kozmiensky, Germany, pp 837–852. ISBN 978-3-935317-92-4
7. Bayerisches Landesamt für Umwelt (LfU) (2012) Restmüllzusammensetzung, Einflussfaktoren, Abhängigkeit von lokalen abfallwirtschaftlichen Rahmenbedingungen – EFRE-Ziel-2-Gebiete in Bayern (Composition of residual waste, influencing factor, dependence on regional waste management framework – EFRE-Goal-2-regions in Bavaria). Eigendruck der Druckerei Bayrisches Landesamt für Umwelt, Augsburg, Germany
8. Mohee R, Mudhoo A (2012) Energy from biomass in Mauritius: overview of research and applications. In: Waste to energy: opportunities and challenges for developing and transitioning economies. Springer-Verlag, London, Great Britain
9. Chen XD, Geng Y, Fujita T (2010) An overview of municipal solid waste management in China. In: Waste management, vol 30. Elsevier Ltd, pp 716–724
10. Raninger B (2009) Management and utilization of municipal and agricultural bioorganic waste in Europe and China. Workshop, Nanyang Technological University, Singapore, China
11. Zhu MH, FanXi M, Rovetta A, He Q, Vicentini F, Liu BK, Giusti A, Liu Y (2009) Municipal solid waste management in Pudong New Area, China. In: Waste management, vol 29. Elsevier Ltd, pp 1227–1233
12. Lianghu S, Huang S, Dongjie N, Xiaoli C, Yongfeng N, Youcai Z (2014) Municipal solid waste management in China. In: Municipal solid waste management in Asia and the Pacific Islands: challenges and strategic solutions. Springer-Verlag, Singapore, China, pp 95–112
13. Linzner R, Salhofer S (2014) Municipal solid waste recycling and the significance of informal sector in China. In: Waste management & research, vol 32. Sage Publications, London, Great Britain, pp 896–907
14. Bonnet M, Viertel JL (2007) Herstellung und Verwertung von Ersatzbrennstoffen unter besonderer Berücksichtigung des Werkstoffes PVC (Production and utilization of refuse-derived fuels by specific consideration of the material grad PVC). In: UmweltMagazin, 03/2007. Springer-VDI-Verlag GmbH & Co. KG, Cologne, Germany, pp 38–40
15. Schingnitz D (2011) Entwicklung eines Schnelltestsystems zur Bestimmung brennstoffrelevanter Parameter von Ersatzbrennstoffen (Development of a rapid test for determination of fuel-relevant parameters of refuse-derived fuels). Dissertation, Technical University of Dresden, Eigenverlag des Forums für Abfallwirtschaft und Altlasten e.V., Pirna, Germany. ISBN 978-3-934253-77-3
16. Sächsisches Landesamt für Umwelt und Geologie (LfUG) (2001) Anlagen zur Verbrennung und mechanisch-biologischen Behandlung von Siedlungsabfällen (Treatment plants for combustion and mechanical biological treatment of municipal solid waste), Dresden, Germany
17. Gehrmann HJ, Seifert H, Beckmann M, Glorius T (2012) Ersatzbrenn-stoffe in der Kraftwerkstechnik (Usage of solid recovered fuels in power plants). In: Chemie Ingenieur Technik, vol 84(7). Wiley-VCH Verlag GmbH & co, KGaA, Weinheim, Germany, pp 1085–1098
18. Tai J, Zhang W, Che Y, Feng D (2011) Municipal solid waste source-separated collection in China: a comparative analysis. In: Waste management, vol 31. Elsevier Ltd, pp 1673–1682

Commingled Waste Collection as Chance for Technical Separation: Alternative Collection Systems

Adele Clausen, Malte Althaus, and Thomas Pretz

Abstract The most relevant parameter for the profitability of a deposit is its raw materials concentration. With the view on secondary raw materials from municipal solid waste (MSW), the concentration depends on the population density and the specific waste generation rate. To recover a secondary raw material from MSW, collection is the first step and at the same time, the bottleneck, as typically the efficiency of the separate collection of recyclables decreases with increasing population density. Also, the effort of collecting many different recyclables as a single fraction, with each of these fractions making up a small specific amount per household, often only leads to collection costs being too high to be compensated by revenues from recycling or waste fees. As a compromise between losing recyclables due to high degrees of contamination when collected in mixed household waste, and exploding collection costs for too many single fractions, recyclables are often collected as a commingled fraction of selected materials, which can technically be efficiently separated, and then be directed to recycling plants. Local waste management structures, such as contractual periods and distribution of responsibilities, lead to specific collection and treatment systems with individual efficiencies, which is demonstrated by different examples, as implemented in Europe.

Keywords Commingled collection, Municipal solid waste, Recyclables, Separate collection, Sorting

A. Clausen (✉), M. Althaus, and T. Pretz
Department of Processing and Recycling, RWTH Aachen University, Aachen, Germany
e-mail: clausen@ifa.rwth-aachen.de

R. Maletz et al. (eds.), *Source Separation and Recycling*,
Hdb Env Chem (2018) 63: 105–118, DOI 10.1007/698_2017_29,
© Springer International Publishing AG 2017, Published online: 29 April 2017

Contents

1 Introduction

The basis for assessing the profitability of mining activities of a specific deposit is the concentration of a resource, e.g. the metal concentration of an ore, compared to the technical effort to get access to the ore. In general, the situation is similar for materials recycling from waste streams: The waste needs to contain a certain concentration of the target material. Thus, several standards have been established by industry defining acceptance criteria for the input material of recycling processes. The European metal industry applies the *European Steel Scrap Specification* [1] for ferrous metals and the *General Terms of Metal Trading* [2] for non-ferrous metals. Both precisely describe different qualities. The same applies to the paper [3], as well as the plastics recycling sector [4].

The standards are always related to quality requirements and the maximum share of impurities that are accepted within a certain quality group. Typically, purity greater than 90% is demanded. As a result, the separate collection of mono fractions is implemented for many production wastes.

If no general trading standards are defined yet, as is the case in the mass sector of construction and demolition (C&D) waste, the recycler directly sets purity demands for the waste flows that he accepts. Driven by economic considerations, the goal of the recycler is the maximum yield of valuables related to a minimum of technical effort.

Also in the field of post-consumer waste, separate collection has been installed for different mono fractions. In Europe, hollow glass is the most dominant example of the implementation of successful single collection.

Even though it is well accepted that recycling requires clean, high quality input materials, commingled collection systems are widely disseminated as well. When commingled collection systems are used, different valuables are gathered in one mixed (commingled) material stream instead of the separate collection of high quality mono fractions. Accordingly, the purity for each of the valuables contained in the commingled material flow is low when compared to materials from a mono collection system. In the following, opportunities and challenges related to commingled collection systems are discussed and evaluated.

2 Collection Systems for Post-consumer Recyclables

When discussing optional collection systems for post-consumer recyclables, the first question to be answered concerns the *valuables* that arise as *waste* in a consumer's household and that are applicable for materials recycling.

In Europe, the amount of municipal solid waste (MSW) typically lies somewhere at about 450 kg per capita per year. MSW includes material groups such as biowaste, paper, wood, textiles, plastics, metals, glass and inert materials such as stone, porcelain or ceramics. Furthermore, waste electric and electronic equipment (WEEE) and bulky waste are part of MSW. A last group to mention contains all materials which cannot be assigned to any of the above. Figure 1 as an example shows the average annual generation of said MSW material groups per capita in Germany.

In terms of evaluating the resource potential of MSW, the decisive number is not the percentage of a valuable material in the total waste material, but the amount of that valuable waste fraction produced per capita [kg/(cap·a)]. This is because the resource must be recovered from the complete settled area and not from a point source, as would be the case for recycling from post-production waste. This means not only that there is a very high number of waste sources, but also that a very high number of individual consumers are participating in the system. Thus, the specific amount per area varies significantly, e.g. due to the varying population density or consumer behaviour.

Typical statistics include total areas. However, the number of people living in the different settlements is much more relevant for the collection task. Figure 2 shows the population density in Europe and in the German federal state of North Rhine-Westphalia.

There are two fundamentally different systems available to gather and collect recyclables, which are called *kerbside collection* and *bring systems*.

Kerbside Collection The consumer provides the generated waste either in bags or in bins at a household level at the kerbside. Depending on the system, the waste is to be gathered as mixed or separated according to different waste types (separation at

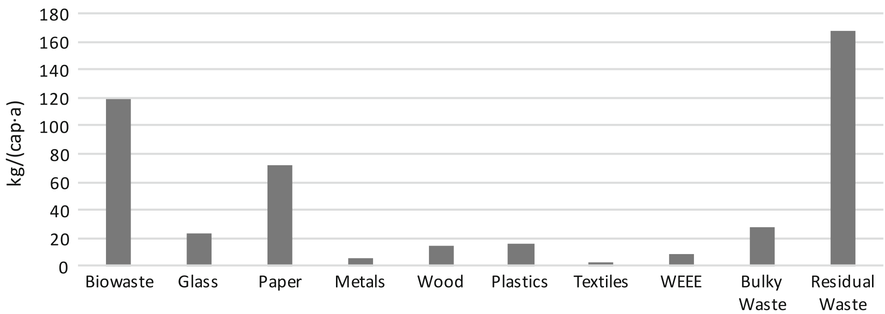

Fig. 1 Average material group distribution in German household waste, 2015 [5, 6]

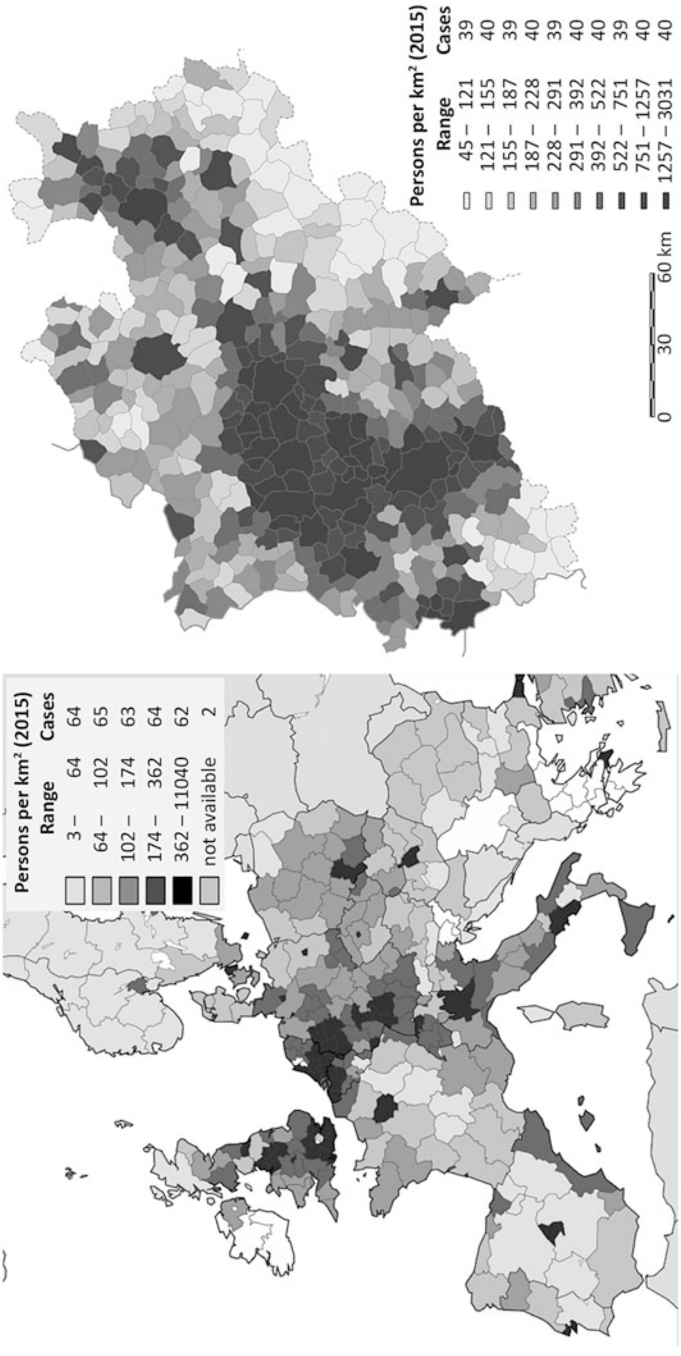

Fig. 2 Population density in Europe by NUTS 2 regions (*left*) [7] and in North Rhine-Westphalia, Germany (*right*) [8]

the source). Typically, different sizes of bins are available according to the settling structure. In densely populated areas with apartment houses, several households typically use bins jointly. Some countries also provide decentralized collection points with bins for several houses (e.g. France, Greece, Spain), so that the consumer has to walk a certain distance to reach the bin. Thus, kerbside collection systems show high variations in terms of user-friendliness.

Bring System Collection points with big containers for recyclables (e.g. 1.1 m^3 containers or depot containers) are installed in decentralized locations for a large number of inhabitants of typically more than 500 up to several thousand. The consumer has to organize the transportation of the waste. The utilization of the system strongly depends on the motivation of the consumer to contribute to a recycling system.

Both kerbside collection and bring systems for pre-sorted recyclables require the participation of informed citizens. The participation rate increases with higher social control, which again is higher the lower the population density is. Accordingly, the separate collection of clean recyclables can be implemented more successfully in rural areas and comes along with lower efficiencies in urban structures. In this case, systems applying technical separation instead of separation at the source can provide an alternative option for implementing pre-sorting. The development of adequate technologies allows not only the recovery of raw materials from highly concentrated yielding of a mono collection, but to also consider waste flows with lower concentrations of valuables, or even mixed MSW (MMSW) as a source of secondary raw materials.

As already mentioned, the key criterion in terms of implementing the separate collection of household waste is the specific waste generation expressed as kilograms per capita and year [kg/(cap·a)]. The second important number is the bulk density of the waste to be collected (kg/m^3). Both information is of special importance for economic considerations. Example data is given in Fig. 3.

3 Commingled Systems

The idea of commingled collection is based on a cost-benefit assessment, whereby an efficient collection of a certain amount of waste per area is evaluated against the remaining technical effort required for technical separation.

When applying mono collection, low specific amounts per inhabitant and year do cause a large collection effort. Also, practical limitations must be considered for the implementation of such systems. A large number of separately collected materials are related to a large number of bags or bins that must not only be stored in the household (Fig. 4, A1/2), but also be placed near the street to be provided for collection by collection trucks (Fig. 4, A3). Both need space to be implemented.

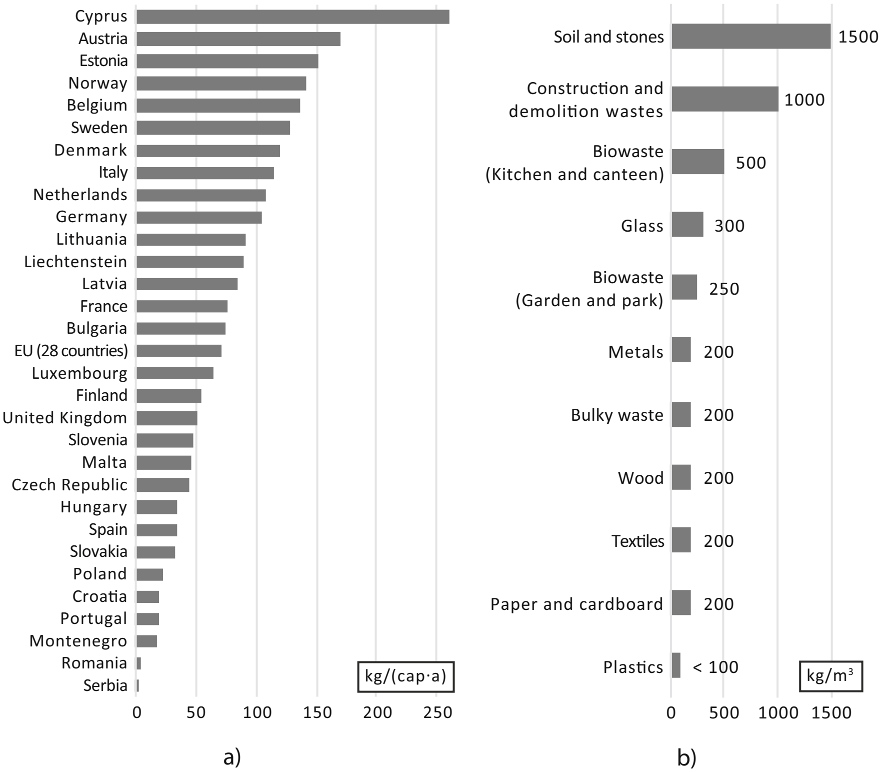

Fig. 3 (**a**) Amounts of recyclables per capita in the EU in 2014 [9]. (**b**) Bulk densities of source-separated recyclables

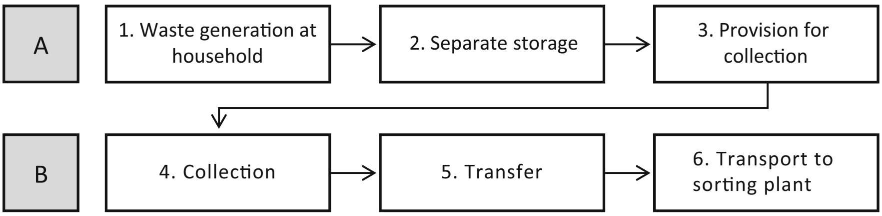

Fig. 4 Process steps of kerbside collection

Hence, part A shown in Fig. 4 is dominated by acceptance and technical feasibility, which is limited especially in high population density, urban areas. Part B, in contrast, can be evaluated solely based on economic considerations.

In order to understand the quantitative contribution of single waste material groups, in the following, the example of *product responsibility* as it is valid for the German packaging market is discussed. Table 1 lists the inhabitant-specific amount

Table 1 Specific amounts of packaging waste

DKR spec.	Name of material fraction	Share in packaging waste (kg/Mg)	Maximum share of impurities (%)	Waste generation[a] [kg/(cap·a)]	Waste generation net[b] [kg/(cap·a)]	Minimum recycling rate[c] (%)	Specific potential [kg/(cap·a)]
320	Plastic bottles	24	6	0.67	0.63	60	1.1
311	Foils >A4	48	8	1.34	1.24	60	2.1
410	Tinplate	106	18	2.97	2.43	70	3.5
420	Aluminium	22	10	0.62	0.55	60	0.9
510	Beverage carton	60	10	1.68	1.51	60	2.5
350	Mixed plastics	204	10	5.71	5.14	60	8.6

[a]Based on an average packaging waste generation of 28 kg/(cap·a)
[b]Content of pure recyclable material assuming the material concentrate contains the maximum of accepted impurities
[c]As defined in the German Packaging Ordinance 07/2014

of waste that is produced and distinguished according to types of packaging. The data are derived from contracts between the operators of sorting facilities and the *Dual System*, which executes the producer's responsibility. To protect from competition, these data are not public. Thus, the data in Table 1 are to be considered as an educated guess.

The share of single material fractions shows considerable deviation depending on specific national consumption patterns. One example is the fraction of beverage cartons. In 2014, the use amounted to 176,000 Mg in Germany, which equals 2.15 kg/(cap·a). After consumption of the content, beverage cartons still contain moisture, and a part of the product typically remains in the packaging as well. On average, these impurities add up to about 25% of the net weight of the beverage carton. As a result, the waste generation rate can be expected to be 2.15 kg/(cap·a) $\times$ 125% $=$ 2.7 kg/(cap·a). For simplification, a value of 2.5 kg/(cap·a) is presented in Table 1.

In the Netherlands, a beverage carton is not only used as packaging for beverages, but also for pasty foods, such as yoghurt or pudding. In 2010, the use of a beverage carton in the Netherlands amounted about 70,000 Mg equalling 4.1 kg/(cap·a). As it is more difficult to completely empty a beverage carton with pasty contents, the share of moisture and remaining product in the beverage carton waste fraction adds up to about 100% compared to the net weight of the beverage carton. Hence, the waste generation rate can be assumed to be as high as 8.2 kg/(cap·a).

The fraction of paper waste, which includes both packaging from paper and printed products, is also subject to national variations in terms of its consumption.

As demonstrated in Fig. 5, which shows the specific paper consumption as well as the specific gross domestic potential (GDP) in different European countries, there is no clear correlation between economic conditions and paper consumption.

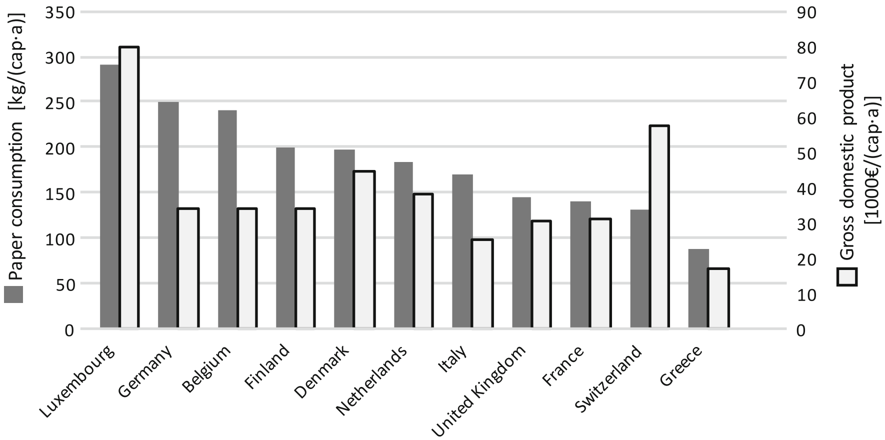

Fig. 5 Paper consumption and GDP per capita in selected European countries, 2014 (Data from paperonweb.com, ec.europa.eu/eurostat/)

In the field of waste paper collection, no differentiation is made between paper packaging and printed products. Also, considering the fact that most of the other types of packaging waste show an even lower bulk density than waste paper, the amount of waste paper available for recycling measures is comparably high.

When developing commingled collection systems, the objective is to combine the operation of a sorting plant under economic conditions with justifiable transport distances.

Mixed packaging waste including printed products shows a low bulk density, which can be assumed to be in a range between 50 and 100 kg/m^3. To avoid long transportation distances with materials having a low bulk density, the first technical process step is organized on a decentralized level.

Under European conditions, the smallest capacity of a sorting plant that is needed to run under economically efficient conditions can be assumed to be at an annual throughput of 100,000 Mg [10]. Applying a decentralized concept, it means that this sorting plant must be reachable by waste collection trucks avoiding a transfer station. The low bulk density of waste packaging material limits the load per waste truck. As a result, from an economic perspective, the radii of collection areas of more than 50 km can hardly be covered. Table 2 demonstrates the area that is required to collect 100,000 Mg/a of input material from an urban and a rural area for both material flows, lightweight packaging (LWP) according to the German system and commingled waste as collected in the UK. At least in rural areas, the waste generation rate per area is too low for an economical collection of LWP.

The example calculations prove the importance of commingled collection systems. They enable the collection of highly inhabitant-specific quantities. In order to implement highly specific collection quantities, paper has to be included in the collection concept as shown in Fig. 6, which compares commingled concepts excluding paper (Germany) and including paper (UK).

Table 2 Required radii of waste collection areas for profitable sorting plants

Collection system	Spatial category	Population density (cap/km^2)	Waste generation [kg/(cap·a)]	Inhabitants generating 100,000 Mg/a (cap)	Radius of required area (km)
LWP Germany	Rural	250	40	2,500,000	56
	Urban	2,000	10	10,000,000	40
Commingled UK	Rural	250	80	1,250,000	40
	Urban	2,000	50	2,000,000	18

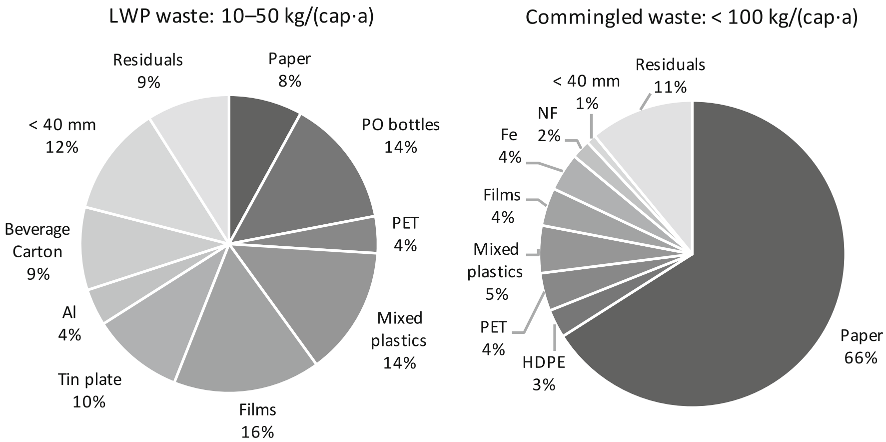

Fig. 6 Amounts and shares of mixed waste collection excluding paper (Germany, *left*) and including paper (UK, *right*)

4 Sorting Technology

The design of sorting plants for mixed waste with a high share of packaging waste always follows the scheme of disintegration first, conditioning second and sorting third. The process of disintegration has to loosen the material mix that has been compacted during collection. Also, packs like bags must be opened. The process of sorting uses particle characteristics. Therefore, relevant particle characteristics may not get lost during the process of comminution. Furthermore, the loosened material mix has to be supplied to the separation processes as an evenly distributed volume flow.

Modern sorting plants for lightweight packaging waste or material recovery facilities (MRF) with a capacity of 100,000 Mg/a realize material throughputs of at least 22 Mg/h. After loosening the material, this mass flow shows a bulk density of between 50 and 100 kg/m^3. Correspondingly, volume flows of 220–240 m^3/h must be processed.

The step of conditioning functions as preparation of the material for the decisive sorting processes. The volume flow is reduced by separating oversized particles.

Screening technology and ballistic separation are applied for that purpose. Furthermore, fine particles are to be removed by screening. This is due to two aspects. The low mass per particle of the fine fraction creates a disproportionally high technical effort per mass to be sorted on the one hand. On the other hand, the share of impurities such as dirt, organics and humidity increases with decreasing particle size. Finally, there are also demands in terms of the particle size distribution and the distribution of the mass per particle of material flow that yield from the separation technology that the material is supplied to in the last steps of the process chain. Thus, the partition of the material into particle size groups is another task that has to be fulfilled during the process step of conditioning.

Special conditions are related to the sorting of packaging waste that contains a high share of paper. In this case, material characteristics such as the stiffness of cardboard and cartons are linked to the particle size. This means that classifying into particle size groups leads to a concentration of materials with similar characteristics in a specific particle size group. Using the example of paper, it is known that the separation of a material flow at a size of DIN A3 (300×400 mm) directs most of the carton into the oversize fraction, and newspaper and journals into fraction <A3. Thus, a separation into material fractions takes place in addition to the separation into particle size groups. Particles of packaging based on metal, paper compounds or plastic that are part of the waste material flow are spread into both intermediate concentrates. A pre-concentration by classifying as described for the group of newspapers and journals and the group of cartons does not take place. Accordingly, these recyclables have to be recovered from different intermediate material flows. Thereby, the parameterization of a sorting process yields from the quality requirements related to the material that dominates the mass flow, e.g. high purity of <1.5 m-% impurities in paper. The separation of material groups that hold a minor share of mass is therefore always conducted in two steps. The objective of the first separation step (*rougher*) is to ensure a maximum yield of the low concentrated target material (e.g. PET), which at the same time functions as a cleaning step for the dominating target material (e.g. paper). The second separation step (*cleaner*) separates impurities. The objective is a high-quality concentrate. This kind of process always yields a loss of target material. This effect can be reduced by applying a third separation step (*scavenger*), which picks the valuables from the rejected material flow. A graphical representation of this separation process is provided in Fig. 7.

If the separation steps described are conducted for all material groups of the material mix, complex process flow charts are derived involving a high amount of sorting equipment.

The most important technology used for comingled sorting today is sensor-based sorting. Modern sensor-based sorting technology separates single particles, which implies that volume flows must be supplied to the sorting equipment as a monolayer of particles to enable individual treatment. This equipment conducts detection, interpretation and separation as three decoupled sub-processes. The interpretation of data allows the application of filters, which again allows the recovery of different qualities.

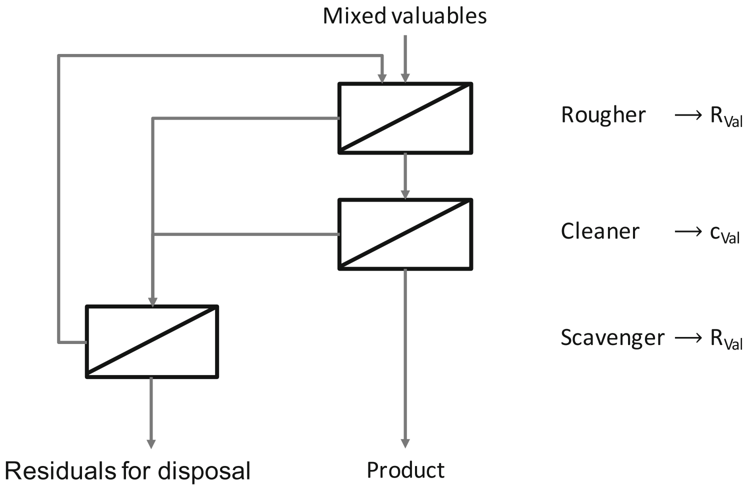

Fig. 7 Separation stages for material groups with small mass fractions

Separation processes based on physical principles combine the identification of a material characteristic with the ejection of the related particle(s). Here, it is possible to modify the product quality by, e.g., adjusting the ejection unit as it can be done for eddy current separators. All separation equipment has the demand that the relation of maximum and minimum particle size in the material flow to be treated in common and is limited to 3:1. The conditioning must ensure the limitation of the grain size range as well as a consistent material distribution in monolayers.

Well-designed treatment processes that are supplied with a mix of pre-sorted recyclables, such as the material collected from commingled systems, enable the realization of high performance parameters. The performance is evaluated by the mass recovery R_M and the yield of valuable target material R_V.

Today, a yield of target material of 90% can be realized for material groups with a particle size of >50 mm if the above-described multi-step sorting processes are applied. The mass recovery quantifies the share of the input material that is recovered as a valuable recyclable product flow and that can be directed to the next stage of the recovery process chain. These recyclable product flows contain impurities according to the accepted maximum.

In contrast to impurities, moisture, product that remained in closed packaging and dirt that is attached to the surface of particles are classified as part of the valuables. Recycling quotas are calculated based on the mass flow that is provided for recycling and also published that way. Hence, a reliable statement about the effectively recycled mass flow cannot be derived from these recycling quotas. Considering the different conditions described, the purity of the recyclable product flows on average adds up to ≥90%, with the exception of paper and tinplate. The purity requirements for paper products can be as high as 99.5% [3]. Tinplate products, in contrast, may contain as much as 33% impurities [4].

5 Techno-Economic Performance

Generally, available technologies allow the separation of recyclables from mixed material flows with a high yield and a high quality that is sufficient for a downstream recycling of the separated recyclable concentrates.

However, quality requirements are often not met or the mass recovery is significantly lower than what the available technology can realize. The reasons are the economic conditions under which commingled sorting plants are operated. They are described in the following:

1. Investment in technical plants or equipment is justified only if a return on investment can be expected. This requires long-term perspectives for a sufficient supply for the sorting plant with an adequate waste material flow, a condition for deciding on an investment. However, the European waste management sector shows a wide spectrum in terms of waste management contracts and durations. These range between 2 years (Germany) and 20 years (Greece), and are accordingly related to a high and, respectively, low supply risk.
2. The demands in terms of quality and quantity aspects of sorting technology are, on the one hand, politically motivated by related laws and directives. On the other hand, they are driven by markets and the markets' demands.

   However, frequent changes in legal demands always trigger technical and operational adaptations in sorting plants, which effect the economic performance of the plant. For example, in Germany the legislation that regulates the recovery of lightweight packaging was revised seven times between 1991 and 2014.

   During the depreciation time of up to 25 years, all processes that take place downstream to sorting were affected by development. At the same time, the input material for sorting plants is subject to changes due to technical developments and consumption patterns. As a result, the quality requirements put on recyclable concentrates are continuously being modified. One example is paper printed with water-soluble ink, which is not permitted to enter a material flow of deinking quality. To fulfil such requirement, a technical adaptation is absolutely necessary.
3. The position of plant operators in recovery chains shows considerable differences. Plant operators can function simply as service providers who are paid per unit at an agreed-on price. The recyclable concentrates remain the property of the customer. However, the disposal of residual waste fractions generated during the sorting process has to be paid. Since the disposal is typically part of the plant operator's service, the costs are covered by the service fee paid by the customer. As a result, the plant operator's motivation to improve the product quality is low, as a higher purity of the product material flow is related to increased mass flows of residual materials and consequently increased disposal costs.

   In contrast, plant operators can hold full economic responsibility for marketing the recyclable concentrates that they produce, as they have to set up bilateral contracts with recyclers, and they have to fulfil the recycler's individual quality demands.

6 Conclusion

One of the main challenges of recycling in the field of post-consumer waste is the fact that a high number of different recyclables are generated with

- a low bulk density
- a low purity
- a low punctual generation rate
- a very high number of sources (=number of inhabitants) that are widespread in the area.

In EU, the sector of packaging waste management is regulated by the EU Directive on Packaging and Packaging Waste [11] which calls for recycling quotas that must be fulfilled applying the approach of producer responsibility. With the private sector being the main player in this business, market mechanisms dominate technical feasibility. The benefit of the separation of recyclables at the source on a household level, which can reduce the required technical effort for sorting, is weighed against the additional effort of separate collection of small quantities with a low weight per volume and resulting huge collecting areas to gather mass flows that justify the operation of a treatment plant. As a compromise, the commingled collection of a mix of selected recyclables is implemented, followed by technical separation. Technically, the separation of mixed recyclables into highly pure mono fractions of valuables with a high mass recovery is feasible. However, again the technical effort realized is driven by market mechanisms. Key elements influencing market conditions are the organization of responsibilities in terms of proving the compliance with quotas, the marketing of recyclable concentrates, the disposal of residual material flows and, crucial for any decision related to investment in technology, the duration of contracts guaranteeing a certain material supply. Short contracts are said to increase competition. However, in the field of household waste recycling, this can also inhibit the implementation of technical development when the economic risk in a volatile market becomes too high for investments.

The design of a commingled collection system is a result of the framework conditions for downstream sorting and recycling activities, which vary greatly in different countries, even among EU countries under the same legislation. High technical efficiency in terms of quality and quantity of recycling is feasible. However, due to different emphases on different values, high technical efficiency is not necessarily what a society may or want to provide a framework for. Therefore, it is crucial to understand how exactly a society defines success in terms of recycling to design adequate framework conditions.

References

1. BDSV (1995) European steel scrap specification. Bundesvereinigung Deutscher Stahlrecycling- und Entsorgungsunternehmen e.V., Düsseldorf
2. VDM (2002) Usancen und Klassifizierungen des Metallhandels [Spec]. Verband Deutscher Metallhändler e.V., Berlin. http://www.metallhandel-online.com/downloads/usancen_2012.pdf
3. CEN (2014) EN 643. Paper and board – European list of standard grades of paper and board for recycling [Standard]. CEN European Committee for Standardization, Brussels
4. DKR (2017) Specifications by Deutsche Gesellschaft für Kreislaufwirtschaft und Rohstoffe mbH, Der Grüne Punkt: DSD – Duales System Holding GmbH & Co.KG [Online]. https://www.gruener-punkt.de/en/download.html
5. AWSAS (2015) Welche Stoffe landen in der Gelben Tonne? Abfallwirtschaft Sachsen-Anhalt Süd [Online]. http://www.awsas.de/content/files/umweltinformation/ui2015-3.pdf
6. Statistisches Bundesamt (2017) Destatis. Table "Aufkommen an Haushaltsabfällen (32121-0001)" [Online]. https://www.destatis.de/
7. European Union (2017) Eurostat. Population density by NUTS 2 region [Online]. http://ec.europa.eu/eurostat/web/products-datasets/product?code=tgs00024
8. IT.NRW (2017) Statistikatlas NRW. Geobasis NRW 2015, IT.NRW 2017. Data licence Germany – attribution – Version 2.0 [Online]. www.govdata.de/dl-de/by-2-0; https://www.statistikatlas.nrw.de
9. European Union (2017) Eurostat. Generation of waste by waste category, hazardousness and NACE Rev. 2 activity [Online]. http://ec.europa.eu/eurostat/web/products-datasets/-/env_wasgen
10. Eule B (2013) In: Pretz T, Quicker P, Wotruba H (eds) Processing of co-mingled recyclate material at UK Material Recycling Facilities (MRF's). Shaker, Aachen. ISBN:978-3-8440-2223-0
11. European Union (2014) Directive 94/62/EC on packaging and packaging waste. s.l.: European Union, 1998–2017. http://eur-lex.europa.eu/

Thermal Treatment as a Chance for Material Recovery

Peter Quicker

Abstract The recovery of materials in the course of thermal waste treatment may sound contradictory at first glance because thermal treatment is supposed to destroy materials. However, this is only the case for organic materials. But waste consists of more: Metals and minerals are part of the trash, and there are options to get them back afterward or better **by** thermal treatment.

This chapter addresses the possibilities for recovering resources for material applications by thermal waste treatment. Two thermal routes are considered: Waste-to-energy (WtE) plants and pyrolytic disintegration approaches.

WtE enables the recovery of iron, nonferrous metals, and also minerals from bottom ash. Another opportunity for material recovery is flue gas utilization. The recovery and material utilization of HCl and sulfur (in the form of gypsum) has been industrially practiced for decades. In the last few years, the first approaches to recover metals from the filter dust were also industrially implemented.

Pyrolytic processes offer the chance to recover valuables from composite material parts, like carbon fiber-reinforced plastics (CFRP), or from metal-enriched fractions of other waste treatment processes like shredder residues. The containing plastics can be volatilized at high temperatures and the emerging pyrolysis gases can be utilized to supply the thermal energy for the process. The absence of oxygen and relatively low temperatures prevents the valuables in the composite matrix from damage.

Keywords Bottom ash, Dry ash discharge, Flue gas cleaning, Material recovery, Pyrolysis

P. Quicker (✉)
RWTH Aachen University, Unit of Technology of Fuels, Wuellnerstrasse 2, 52062 Aachen, Germany
e-mail: quicker@teer.rwth-aachen.de

R. Maletz et al. (eds.), *Source Separation and Recycling*, Hdb Env Chem (2018) 63: 119–150, DOI 10.1007/698_2017_28,
© Springer International Publishing AG 2017, Published online: 18 May 2017

Contents

Abbreviations

CFB	Circulating fluidized bed (reactor)
CFRP	Carbon fiber-reinforced plastics
DM	Dry matter
DOC	Dissolved organic carbon
FGC	Flue gas cleaning
KEZO	Kehrichtverwertung Zürcher Oberland (WtE plant in the Zurich region)
MSW	Municipal solid waste
MSWI	Municipal solid waste incineration
RDF	Refuse-derived fuel
SCR	Selective catalytic reduction (of nitrogen oxides)
SNCR	Selective non-catalytic reduction (of nitrogen oxides)
SRF	Solid recovered fuel
WEEE	Waste electrical and electronic equipment
WtE	Waste-to-energy

1 Introduction

The subject of this section is the recovery of materials in the course of the thermal treatment of waste. This may sound contradictory at first glance. Thermal treatment is supposed to destroy materials. However, this is only the case for organic material. But waste consists of more. Metals and minerals are part of the garbage, and there are options to get them back afterward or better **by** thermal treatment.

Figure 1 gives an overview of the basic process concepts for the thermal treatment of waste. The state of the art for the treatment of municipal solid waste (MSW) is combustion, directly in waste-to-energy (WtE) plants, or after a pretreatment process, as so-called refuse-derived fuels (RDF), by mono-incineration in RDF power plants, or by co-combustion in cement kilns or coal power plants.

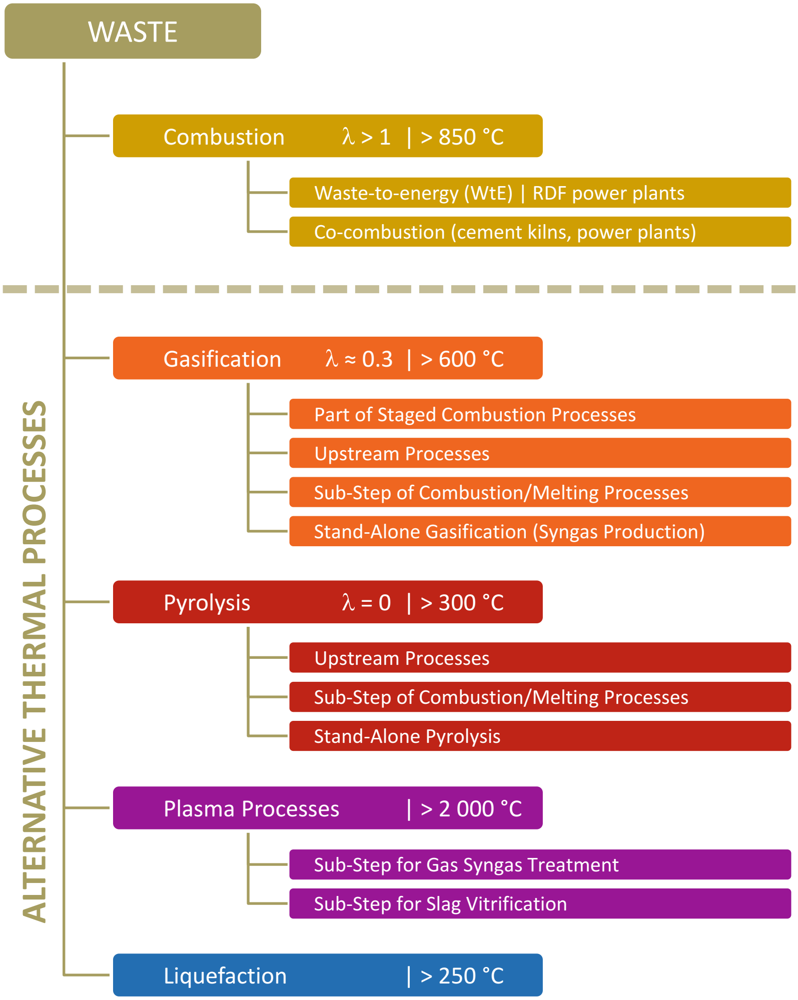

Fig. 1 Overview of thermal processes for waste treatment [1]

The possibilities for material recovery from WtE plants are presented in Sect. 2. The options are the utilization of fractions from bottom ash (especially metals) and the generation of valuables (HCl, gypsum, and zinc) from the flue gas.

Material recovery by the co-combustion of waste is not discussed deeper in this chapter. In such facilities, the material utilization of the co-combusted waste (e.g., RDF, sewage sludge, animal meal, waste oil, etc.) is restricted to its ash content, which ends in both co-incineration processes as an additive in cement production. In cement kilns, (preprocessed) waste is used as a solid recovered fuel (SRF) to supply the heat for the energy consuming burning of the clinker. The containing ash remains in the kiln and becomes a part of the product. The fly ash from coal power plants is normally used as an aggregate for mixing with the cement clinker. In both cases, the share of the mineral fraction in the final cement product originating from the waste is marginal. Therefore, the composition of the waste does not normally influence the product properties if reasonable quality management for SRF and RDF is provided.

In Fig. 1, the so-called alternative thermal waste treatment technologies are also listed. The adjective "alternative" in this context refers to incineration. That means all thermal processes which are not combustion (i.e., which are not operated with excess oxygen) are labeled with this term. Gasification and pyrolysis are the most popular "alternatives." More novel approaches are plasma processes, operated at very high temperatures, which are generated by the use of electricity, or liquefaction procedures, which are supposed to supply high quality liquid fuels from solid waste by conversion in an oily liquid medium. Due to their limited technical relevance for waste treatment in Germany and Europe (which is supposed to also be the case in the future), the options to recover material products from gasification, plasma processes, and liquefaction are not discussed further here. A detailed evaluation of those processes can be found elsewhere [1].

In contrast to the aforementioned alternative thermal waste treatment technologies, processes on the basis of pyrolysis offer interesting options for material recovery from special fractions (but not from MSW). This thermochemical approach is an efficient tool for the treatment of composite structures with valuables in a matrix of other components (normally plastics or resins). The plastics can be volatilized at higher temperatures and the emerging pyrolysis gases can be combusted to generate the heat for the process (condensation and material utilization of the pyrolysis liquids is not recommended due to the difficult processing and poor properties of such liquids). The remaining valuables, e.g., metals, carbon fibers, etc., may be of high quality due to the inert atmosphere during treatment in the absence of oxygen. Examples for the recovery of valuables from composite waste fractions by pyrolysis are given in Sect. 3.

2 Material Recovery from Waste-to-Energy Plants

The principle structure of all state-of-the-art WtE plants is similar (cf. Fig. 2): MSW and commercial waste is delivered by truck (sometimes also by train or ship) and dumped into an underground bunker. The waste is mixed and fed via crane and feed hopper into the furnace. The vast majority of the WtE plants are equipped with grate furnaces. Forward and backward pushing configurations as well as roller grate systems are in use. Bottom ash and raw flue gas, including solids and gaseous pollutants, are the two product streams out of the incinerator, which offer the potential for material recovery. Typical compositions of residues from MSWI are given in Table 1.

The bottom ash can be discharged from the furnace by wet or dry operated systems (cf. Sect. 2.1.1) and the subsequent processing can be operated wet or dry

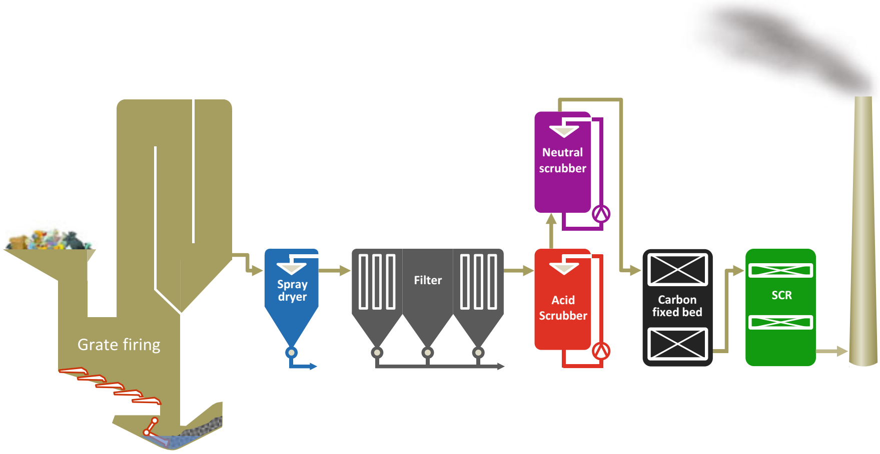

Fig. 2 Diagram of a typical waste-to-energy (WtE) plant with wet flue gas treatment system and selective catalytic reduction (SCR)

Table 1 Composition (main components) of residues from MSWI in wt.-% (dust collector, wet scrubber, milk-of-lime neutralization, and scrubber effluent evaporation [3])

Components	Bottom ash	Ash and dust from boiler and flue gas cleaning system	Reaction salts from scrubber effluent evaporation
Al_2O_3	5.7–8.1	5.1–18.0	2.1–3.1
CaO	8.7–21.3	6.5–30.0	29.4–46
Fe_2O_3	3.0–14.2	1.6–6.5	1.1–1.3
SiO_2	45.7–60.1	12.5–54.7	5.0–5.1
Chloride	0.2–0.3	6.5–8.2	17–32 (26–50% $CaCl_2$)
Sulfate	0.1–2.7	2–4	4.3–15.0 (18–64% $CaSO_4$)

also. The processing goals are the recovery of iron and nonferrous metals, as well as at the production of mineral fractions, which can be used as construction materials. The processing of bottom ash and the subsequent recovery of valuables are discussed in Sect. 2.1.2.

The heat from the flue gas is recovered by a water tube boiler and the gas is thereby cooled down to temperatures of about 180–230°C. Subsequently, the pollutants – heavy metals, organic substances, acidic gases, nitrogen oxides (may also be reduced by selective non-catalytic reduction (SNCR) already in the boiler), and dust – are eliminated from the flue gas before they are released into the atmosphere through a chimney. The installations for flue gas cleaning can be classified as dry, conditioned dry, and wet systems, as defined in Fig. 12. The prerequisite for the recovery of products from the flue gas – hydrochloric acid, gypsum, or metals from the flue dust – is the application of a wet cleaning system, as it is depicted in Fig. 2. The possibilities for material recovery from the flue gas of MSWI are described in Sect. 2.2.

RDF power plants are technically configured in a very similar manner as WtE plants. Regarding the furnace, some fluidized bed incineration systems are in operation, but most installations are equipped with grate firing. The character of the ash from both furnace types and the methods for processing them are similar to those of WtE plants. Usually the metal and mineral content in RDF is lower compared to MSW because of the preprocessing of the RDF (which implies the separation of metals), but the quality of the products is comparable to WtE plants. Recovery of products from the flue gas cleaning systems is not common in RDF plants because these plants are normally equipped with (economically advantageous) dry flue gas cleaning systems.

2.1 Material Recovery from Bottom Ash

The material utilization of bottom ash from waste incineration is almost as old as waste incineration itself. The first German waste incineration plant, put into operation in Hamburg Bullerdeich in 1896, was already equipped with a magnet to separate the iron (which was sold for 15 Reichsmarks per ton) from the bottom ash. But not only the metal was recovered in these old times, the mineral fraction was utilized also. This was common practice in plants over the whole of Europe (cf. Fig. 3). The city council of Brno, for example, decreed in the beginning of the twentieth century that the mineral fraction from the local waste incineration plant had to be used mandatorily as a substitute for sand in public buildings [4].

The inorganic fraction in the waste amounts to about 25–35 wt.-%. Hence, bottom ash is the most relevant product stream from WtE plants [5]. In Germany

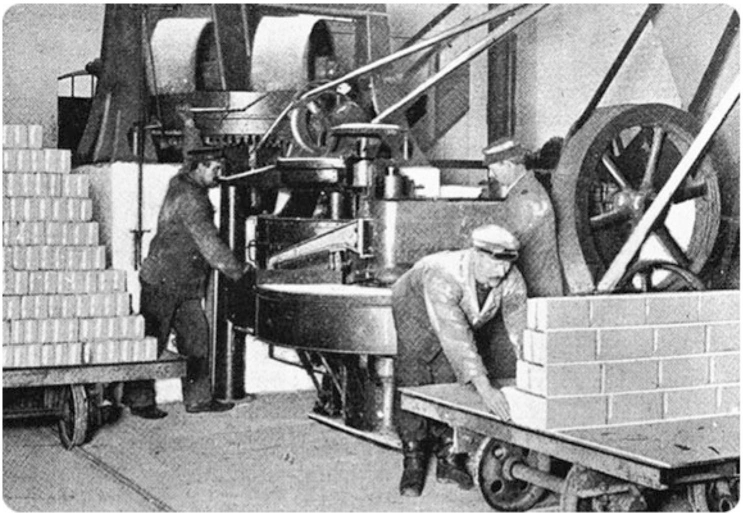

Fig. 3 Fabrication of bricks from bottom ash at the beginning of the twentieth century [4]

in 2013, about 5.35 million tons of bottom ashes were generated [6]. The average composition of this ash can be specified as follows [7]:

- 45 wt.-% ash and slag <2 mm
- 40 wt.-% course melted aggregates (oxides and silicates)
- 10 wt.-% original mineral materials (fragments from glass, ceramics, and stone)
- 6 wt.-% metals
- 1–2 wt.-% unburned components

Recent studies showed that the metal content in MSW decreased in Germany within the past three decades. Analyses carried out in the last 10–15 years resulted in metal contents of between 1 and 3.5 wt.-% of the residual waste in Germany. In commercial and bulky waste, metal content between 3 and 7 wt.-% was found. A survey among the operators of bottom ash processing plants in Germany, referring to 2014, which represented 4.4 million tons and therefore 80% of the bottom ash generated in Germany, showed that 1.3 wt.-% of nonferrous metals and 7.7 wt.-% iron scrap could be recovered on average. The amount of unburned material amounted to 0.9 wt.-% [8].

Despite the decreasing metal content, an extensive treatment of the bottom ash, with a focus on the recovery of the metals, is nowadays state of the art. Especially in the last decade, the technologies for the recovery of metals have made great progress. The processes became more and more sophisticated and the treated grain sizes smaller (down to 0.25 mm). Some new processes were developed, which enhanced the metal recovery by applying crushing steps to destroy the agglomerates in the ash. This results in the disintegration of the mineral fraction, which on the other hand impairs the building properties of this material.

The following sections give an overview of technologies for bottom ash discharge and processing. The current state is described below and some interesting new approaches are presented.

2.1.1 Bottom Ash Removal

The state of the art and therefore applied in the vast majority of the WtE plants installed worldwide is the wet discharge of the bottom ash. In Switzerland and also in Japan, some plants are operated with dry discharge systems, which are supposed to enhance the quality and quantity of metal recovery.

Wet Bottom Ash Discharge

Wet bottom ash discharge means that the ash falls from the grate directly into a water bath (cf. Fig. 4). The water bath has two functions: it cools the hot ash and seals the furnace from the ambience to keep the desired underpressure within the combustion chamber. Further advantages of the wet operation are the prevention of dust during ash handling and the destruction of sintered agglomerates by the rapid

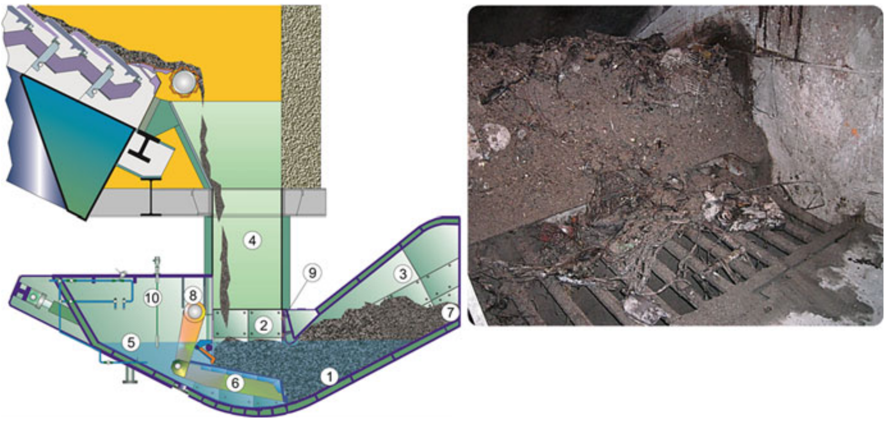

Fig. 4 *Left*: scheme of a wet type bottom ash ram discharger. 1 – Discharger tub, 2 – Inlet section, 3 – Outlet chute, 4 – Connecting piece, 5 – Water level, 6 – Discharge ram, 7 – Drop-off edge, 8 – Drive shaft, 9 – Air sealing wall, and 10 – Electrically controlled level metering system (Copyright Martin GmbH für Umwelt- und Energietechnik, Munich). *Right*: outlet of a wet type bottom ash ram discharger with screen for the separation of coarse material (Photo Peter Quicker)

quenching of the material (result of thermal tensions between cool water bath and hot agglomerates). Disadvantageous is the initiation of hydration, sulfatization, salt building, and solution reactions from the contact with water. This results in a solidification (hydraulic reactions) of the ash, which hampers the following processing.

The installed bottom ash discharge systems differ in the way they remove the ash from the water bath. Plate and chain conveyors are possible solutions, but predominantly ram dischargers are applied (cf. Fig. 4). The ram (no. 6) periodically pushes the ash through the outlet chute (no. 3) out of the water bath into a container, or onto a conveyor belt (the photo shows a rod screen to separate coarse material). During its residence time at the "drop-off-edge" of the discharger (no. 7), the material is dewatered. The water level in the tub has to reach the air sealing wall (no. 9) to ensure the tightening of the furnace.

Dry Bottom Ash Discharge

The first trials with dry bottom ash discharge were carried out in the 1990s by the companies ABB and Martin GmbH. In Japan and also in Switzerland (Hinwil, Monthey, Zurich, Horgen, and in Zuchwil, in combination with a wet discharge), dry discharge systems are in industrial operation. The companies have implemented different approaches to cool down the hot ash and to handle the strong dust formation.

Figure 5 shows the dry discharging system applied in the KEZO Hinwil WtE plant in the region of Zurich. A central element of the ash removal system is a vibrating channel [9, 10]. After burnout, the ash falls down from the grate into the channel. The dropping impact results in a crushing of agglomerates. The ash is

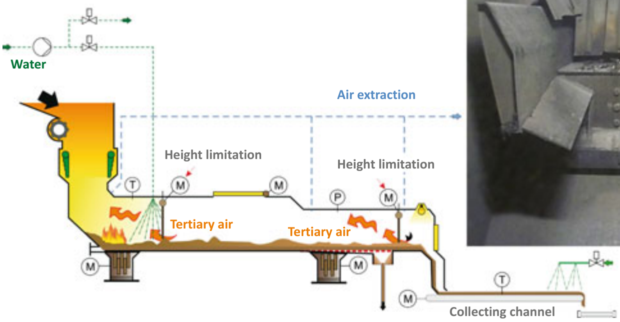

Fig. 5 *Left*: scheme of the dry bottom ash discharger in Hinwil, Switzerland (Copyright KEZO). *Right*: outlet of the dry bottom ash discharger (Photo Peter Quicker)

transported through the channel onto an integrated 5 mm screen by vibration and is cooled down by a countercurrent airstream [9, 11]. After passing the vibrating channel, the air enters the furnace and substitutes about 10% of the combustion air [12]. This so-called tertiary air has multiple functions [9, 12]:

- The bottom ash is cooled and the air concurrently warmed up. The sensible heat of the bottom ash is hereby recovered and reverted to the furnace. In comparison to the wet discharge process, where the heat is lost through the cooling of the ash in the water bath, the thermal efficiency of the process is (slightly) increased.
- The air oxidizes unburned material in the bottom ash. Typical TOC values are below 0.3%.
- The air generates a screening effect and transports fine particulates back into the furnace.

Advantages named by the operator are the saving of approximately 70–100 L of water per ton of waste, the reduction of the total mass of the bottom ash of about 20 wt.-%, because of the absence of water, and – as the main point for the following ash processing and metal recovery – the creation of better bulk material characteristics (no hydraulic solidification reactions) [9].

Other systems for the dry bottom ash discharge were developed by the companies Martin GmbH and Hitachi Zosen Inova (HZI). Whereas HZI also uses a channel for discharge, the Martin system combines an air classifier with a dry operated ram discharger, like the one depicted in Fig. 4 [13–17].

2.1.2 Bottom Ash Processing

The following sections (sections "State of the Art" to "Optimization of Mineral Fraction") refer to the processing of wet discharged bottom ash. The first section gives an overview of state-of-the-art technology for the dry and wet processing of wet discharged ash. The two following sections highlight the possibilities to optimize the recovery of metals and minerals. Finally, section "Processing of Dry Discharged Bottom Ash" deals with the processing of dry discharged ash.

State of the Art

Bottom ash processing in Germany is undertaken by some of the WtE plant operators by themselves, but to a greater extent by independent, external bottom ash processing companies. State of the art and applied in most of the processing facilities are dry operated systems. The main focus of the operators is metal recovery. Therefore, a multitude of separation steps is applied, e.g., up to 12 separators for nonferrous metals in one facility (maximum value). In Fig. 6, an exemplary process

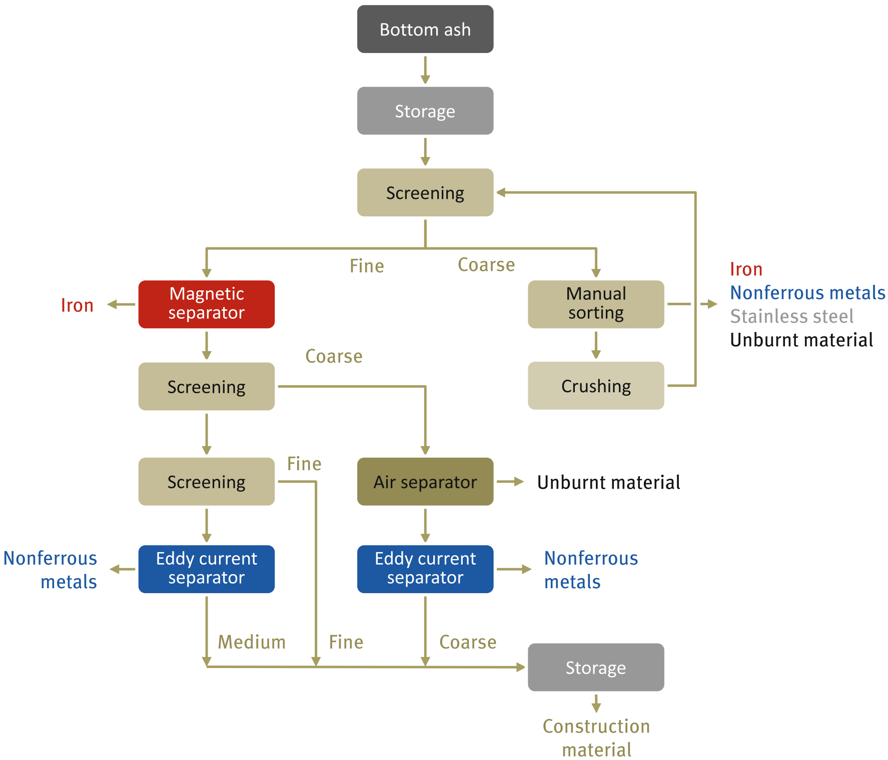

Fig. 6 Exemplary plant setup for the processing of wet discharged bottom ash from municipal solid waste incineration (MSWI) on the basis of [2, 11, 18–21]

Fig. 7 Bottom ash processing plant of the company Scherer und Kohl in Ludwigshafen. *Left*: processing machinery, *middle*: produced gravel fraction, and *right*: sludge filter cake (Photos Peter Quicker)

scheme for dry bottom ash processing is given. Modern plants create more grain-size fractions because the efficiency of metal recovery can be increased by narrow grain-size corridors. Further information about details of bottom ash processing technologies can be found elsewhere [18, 22].

Only few facilities in Germany are applying wet processes for bottom ash treatment. The company Scherer und Kohl in Ludwigshafen has a long tradition in this field. The company's process comprises a dry preconditioning and a wet processing of the fine fraction smaller than 22 mm. Firstly, iron scrap and coarse components (>56 mm) are separated. Afterward, the remaining material (predominantly minerals) is crushed by an impact mill to grain sizes below 22 mm. This material is further treated in the wet processing part of the plant. Products – besides iron and nonferrous metals – are substitute construction materials with defined grain sizes (2–5, 5–8, and 8–16 mm) and high quality (cf. eluate parameters "S&K" in Table 2). About 70% of the whole material can be used as construction material. Only about 6–7% of the inputs have to be landfilled as sludge [28] (Fig. 7).

Optimization of Metal Recovery

As already mentioned, metal recovery is the main target for bottom ash processing, because the metals offer an additional income for the operators besides the tipping fee for accepting the ash. Against this background, it is not surprising that some new processes with enhanced metal yields have been developed within the last few years.

The Advanced Dry Recovery (ADR) process was developed in a cooperation between the Technical University of Delft and the company Inashco BV. The innovation of this process is a dry mechanical fractionation step by application of a rotating drum. It could be demonstrated that the aluminum recovery rate of the process is significantly higher compared to conventional technology. In the meantime, several industrial ADR plants are in operation, treating 2.5 million tons of bottom ash altogether per year [29–31].

Table 2 Eluate parameters of bottom ash dependent on discharging type, state of aging, and way of (further) processing

State of aging		Fresh				Aged			Processed		Rules	
Type of discharging		Wet			Dry	Wet		Dry	Wet	Wet		
									S&K	SYN+	LAGA	NRW
		n.s.	2005	2008	1999	2005	2008	2014	2004		2003	2001
Processing		[23]	[24]	[23]	[25]	[24]	[23]	[2, 23]	[26]		[27]	[24]
Parameter	Unit											
pH value		11.6	11.8	11.9	12–12.4	11	10.3	10.3–11.9	bld	n.s.	7–13	7–13
Conductivity	mS/cm	**5**	**2.4**	**6**	3.3–4.8	1.5	**2.2**	0.7–3.4	bld	0.27	6	2
DOC	mg/l	14	34	26	5–103	16	16	3.5–140	bld	n.s.		
Chloride	mg/l	**150**	**150**	**650**	**250–284**	**120**	**260**	**68–335**	29	22	250	50
Sulfate	mg/l	**330**	**220**	**460**	19–122	**250**	**370**	95–**609**	43	n.s.	600	200
Cyanide tot.	µg/l	60	5	20	<10	5	12	k.A.	bld	n.s.		
Arsenic	µg/l	4	10	4.5	<1	10	13	<10	1.3	<10		
Lead	µg/l	**1,500**	**450**	**2,000**	**167–1,030**	12	**70**	5–**286**	bld	<10	50	50
Cadmium	µg/l	2	n.s.	**13**	<0.2–1.5	**10**	1.3	0.3–1	bld	<1	5	5
Chrome tot.	µg/l	23	30	25	41–**123**	43	**70**	5–14	bld	<10	200	50
Copper	µg/l	150	**450**	**500**	26.4–**337**	250	200	10–236	bld	30	300	
Nickel	µg/l	30	10	15	3.3–11.1	10	**500**	4–8	bld	<20	40	
Mercury	µg/l	0.6	**1.3**	0.85	<**2**	0.15	0.35	0.1–0.2	bld	0.2	1	1
Zinc	µg/l	250	60	**500**	106–200	20	90	10–40	bld	40	300	300

bld below limit of detection, *n.s.* not specified, *S + K* wet bottom ash processing according to the process of the Scherer + Kohl company, Ludwigshafen, *SYN+* processing according to the SYNCOM-Plus process of the Martin GmbH company, Munich, *LAGA* LAGA technical bulletin (Merkblatt) M20, *NRW* recovery decree of North Rhine-Westphalia

Another product of corporative research is the ATR[1] process, developed by several industrial, public, and academic partners. This concept is based on the application of a high-velocity impact crushing device (impact velocities of 800 km/h), which allows the disintegration of the agglomerates and thereby the recovery of the embedded metals. More than 50% of the material is crushed to get sizes smaller than 2 mm by this procedure [32–35].

Other approaches to enhance the metal recovery from MSWI bottom ash include the VeMRec-process, developed by the Institute for Recycling at RWTH Aachen University [36] or the ReNe-process, designed by the Technical University of Clausthal [37, 38].

Optimization of Mineral Fraction

The mineral fraction in the bottom ash shows parameters which hamper the utilization of the material for construction purposes. Besides structural properties, influencing the construction stability, particularly the elution behavior of the material, is of high importance. Only if the legal requirements are fulfilled and the elution values of heavy metals fall below the limits, an application of the material in construction is possible.

Table 2 shows typical eluate values for different types of bottom ash: wet and dry discharged, fresh and aged as well as processed by a wet system (Scherer und Kohl, cf. section "State of the Art") and "pretreated" by the SYNCOM-Plus process (see below). For comparison, the limits from two German regulations are also given.

All values exceeding the limits of at least one of those regulations are marked in bold. Wet and dry discharged, as well as fresh and aged bottom ashes without processing, show several values higher than prescribed in the regulations. It is clearly visible that only the processed mineral fractions can fulfill the rules. Therefore, influencing the elution behavior of bottom ash from MSWI was and is a topic of research and development. There are several possibilities for enhancing the elution behavior of bottom ash besides the already discussed wet processing. Solidification processes use binder materials to immobilize the heavy metals. Sintering and melting processes apply higher temperatures to induce structural modifications in the mineral matrix to reach the same goal.

A thermal treatment subsequent to the incineration process, with the already cooled bottom ash, is very energy demanding. It is more reasonable from an energetic point of view, to design the incineration process in a way that allows the melting or sintering of the bottom ash directly in the furnace. An example of such an approach is the SYNCOM process, developed by the company Martin GmbH and realized in the MSWI facility in Arnoldstein, Austria (Figure 8 shows the scheme of the SYNCOM-Plus process, which consists of an integrated washing step for bottom ash in addition to the sintering step). The necessary sintering temperature of 1,150°C is reached by

[1]ATR for German: **A**ufschluss (disintegration), **T**rennung (separation) and **R**ecycling.

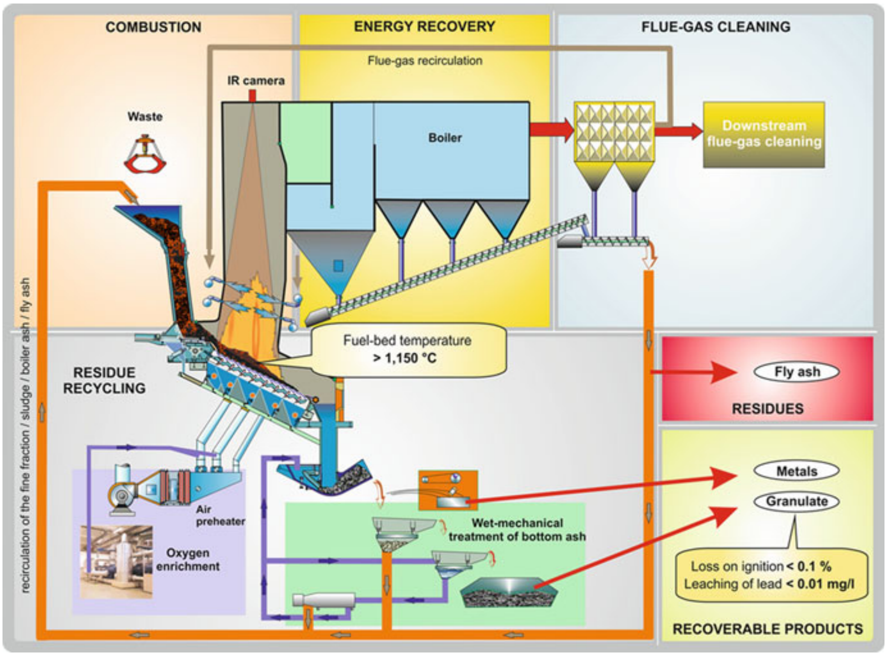

Fig. 8 Scheme of the SYNCOM-Plus process, designed by MARTIN GmbH für Umwelt- und Energietechnik, Munich (Copyright Martin GmbH)

enrichment of the combustion air with oxygen. The sintering process results in a reduction in the fine fraction in the bottom ash and decreases the extractability of the heavy metals and anions from the mineral fraction (cf. Table 2) [39, 40].

Processes with integrated washing steps focus on the leaching of the heavy metals instead of a demobilization. An example is the already discussed process of the Scherer und Kohl company (cf. section "State of the Art" and Table 2). An elution of the heavy metals can also be carried out directly into the wet operated bottom ash discharger if it is operated with increased water throughput. It is thereby possible to reduce the chloride and sulfate eluate concentrations by about 50% [41].

A washing step is also included in the SYNCOM-Plus process (cf. Fig. 8) in combination with the already explained sintering step (SYNCOM process). The partly sintered bottom ash is washed, screened, and a granulate with a high leaching stability is produced (cf. Table 2). During screening and washing, a fine fraction and a sludge are generated. Both are recycled to the bunker and fed into the incineration process again to form agglomerates, and thereby reduce the share of fine particles in the bottom ash [40]. The granulate product as well as the fine fraction and the sludge are pictured in Fig. 9.

Fig. 9 Granulate product from SYNCOM-Plus process (*right*) and sludge, as well as fine fraction for recycling in the incineration process (Photos Peter Quicker)

Processing of Dry Discharged Bottom Ash

The development and implementation of new dry operated bottom ash discharge systems also necessitates new processing approaches for the ash. As for the dry discharge systems, in Europe, these facilities can only be found in Switzerland.

The dry discharged bottom ash in the MSWI plant in Monthey is processed in the same facility formerly used for the wet discharged bottom ash. Only the eddy current separators had been optimized by the operator [14]. It is obvious that a further adjustment of the processing technology would result in an increase in the metal yield. The operator intends to realize this potential [14].

In the incineration plant in Hinwil (KEZO), in contrast, a totally newly developed processing system for the dry discharged ash was installed. Through the application of conventional but optimized processing steps, it was possible to treat bottom ash fractions down to 0.2 mm. It was stated by the operator that a 90% recovery of nonferrous metals could be reached [9, 42, 43].

The question currently discussed, whether dry bottom ash discharge can enhance the yield and quality of the recovered metals from bottom ash in comparison to wet discharge systems, was investigated in a project funded by the German Federal Environmental Agency [2]: In the WtE plant in Mainz, the wet and dry (the normally wet operated ram discharger was run without water filling) discharge of bottom ash was realized on two subsequent days at the same line, and 10 tons of bottom ash were extracted each day. Both materials were processed according to the state of the art (top belt magnetic separator, magnetic drum separator, and eddy current separator), with special focus on a deep fractioning of the material (fractions: 0–2 | 2–4 | 4–10 | 10–30 | 30–80 | >80 mm), to enhance the metal recovery (Fig. 10).

It could be shown that by application of the same processing and separation steps, the share of nonferrous metals that could be recovered from the bottom ash was significantly higher for the dry discharged material. Furthermore, the qualities of the metals were better because of the absence of products from oxidation processes and hydraulic reactions (cf. Fig. 11).

Nevertheless, it has to be mentioned that similar yields may also be extracted from wet discharged material with special adapted technologies. This is at the moment being investigated in a project in Switzerland [44].

2.2 *Material Recovery from Flue Gas*

The second product stream of waste incineration, besides the bottom ash, is the flue gas. It is possible, and has already been realized, to recover resources from this output stream as well. Valuable materials can be recovered from the particles (dust) as well as from the gaseous components. Table 3 shows the concentration ranges of the main components in the raw gas of waste incineration facilities.

Dominant components in the flue gas are particles (dust), HCl, and sulfur dioxide. The recovery and material utilization of HCl and sulfur (in the form of gypsum) has been practiced industrially for decades (cf. Sects. 2.2.2 and 2.2.3).

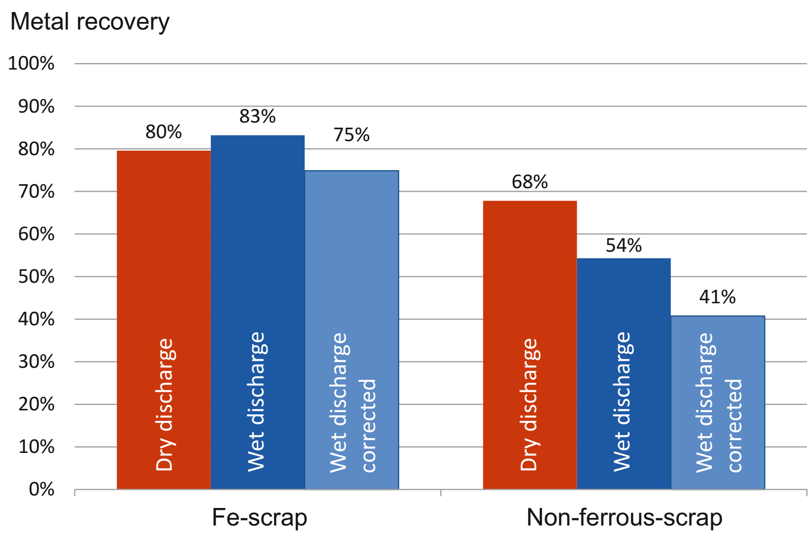

Fig. 10 A comparison of metal yield through the mechanical processing of dry and wet discharged bottom ash. According to the lower product quality, the yields of metals from wet discharge were corrected by an empirical factor (Fe: 10%, NE: 25%), according to the experience of the authors [2]

Fig. 11 Iron product from dry (*left*) and wet (*right*) discharge of MSWI bottom ash

Table 3 Main components in raw and clean gases of waste incineration plants (daily average values)

Component	Raw gas [$mg/m^3_{i.N., 11\% O2, dry}$]	Clean off gas [$mg/m^3_{i.N., 11\% O2, dry}$]
Dust	600–5,000 (15,000)	0.1–2
Total organic carbon	10–40	0.1–2
Carbon monoxide (CO)[a]	2–30	
Hydrochloric acid (HCl)	400–2,000 (5,000)	0.02–7
Hydrofluoric acid (HF)	2–30	0.02–0.5
Sulfur dioxide (SO_2)	100–1,500	0.1–30
Nitrogen oxides (as NO_2)	200–500	30–190
Mercury (Hg)	0.1–1	0.0002–0.01
PCDD/PCDF [$ng/m^3_{i.N., 11\% O2, dry}$]	3–6 (15)	0.001–0.05

[a]Carbon monoxide is not reduced within the flue gas treatment and therefore raw and clean gas values do not differ

New approaches focus on the recovery of metals from the dust in the flue gas. The dust is a variable mixture of different particulate components and contains noticeable amounts of metals that can be recovered (cf. Sect. 2.2.4) (Table 4).

2.2.1 Flue Gas Cleaning Systems

As already mentioned, a variety of different flue gas cleaning systems for WtE plants exist regarding the separation of the acidic gases. Figure 12 gives an overview of typical solutions (according to VDI 3460 [3]).

Dry and conditioned dry flue gas cleaning processes have the common disadvantage that dust and flue gas cleaning residues are collected at the same point (dust filter). This complicates an effective recovery of resources.

Wet flue gas treatment systems normally consist of an acid and a neutral washing stage. This allows the stepwise and more or less selective extraction of chlorine and

Table 4 Composition of the metal fraction in filter dust from Swiss MSWI plants [45]

Component	Mass concentration [mg/kg DM]			Mass concentration [mg/kg DM]	
	Minimum	Maximum		Minimum	Maximum
Aluminum	25,000	45,000	Magnesium	6,000	18,000
Antimony	700	5,000	Manganese	400	900
Arsenic	20	120	Sodium	25,000	70,000
Barium	50	200	Nickel	60	300
Lead	7,000	25,000	Phosphor	1,000	8,000
Cadmium	150	1,000	Mercury	0	3
Calcium	100,000	250,000	Sulfur	30,000	150,000
Chlorine	40,000	150,000	Silver	30	60
Chrome	100	500	Silicon	50,000	100,000
Cobalt	20	100	Titanium	2,500	5,000
Iron	18,000	55,000	Zinc	20,000	120,000
Potassium	30,000	60,000	Tin	800	3,000
Copper	1,500	5,000			

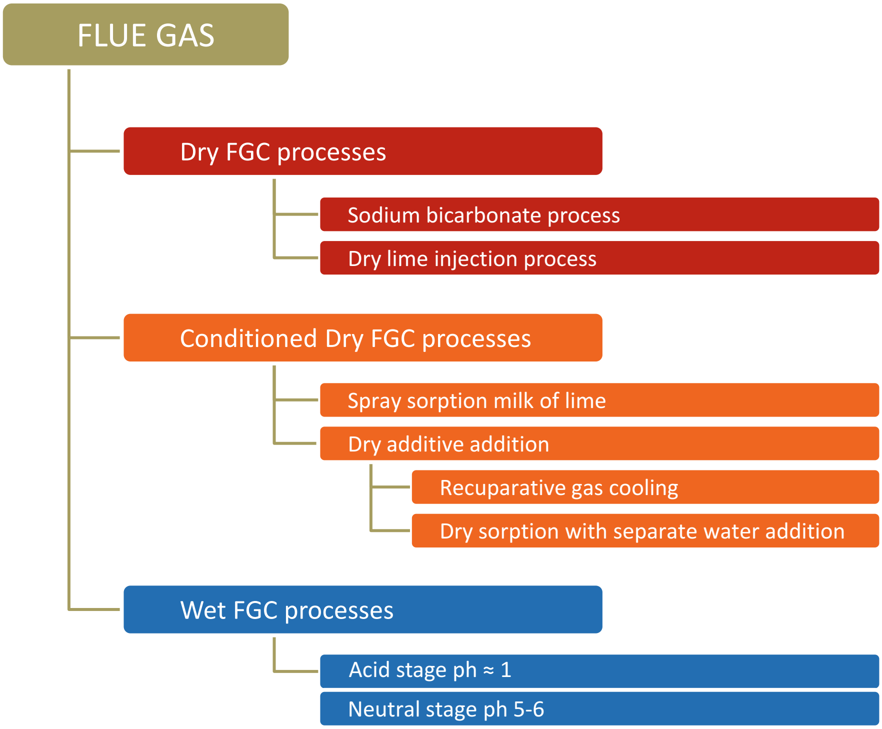

Fig. 12 Classification of flue gas cleaning systems in waste incineration plants according to VDI guideline 3460 Emission control – Thermal waste treatment [3, 46]

sulfur from the flue gas as a basis for the further material utilization of these components.

Further information regarding the flue gas cleaning systems of solid waste incineration plants can be found elsewhere [46]. The following paragraphs give a short overview of the currently existing and applied technologies for the recovery of valuables from the flue gas of WtE plants.

2.2.2 Recovery of Hydrochloric Acid

The requirement for the recovery of HCl from flue gases of municipal solid waste incineration (MSWI) is the deposition of the dust prior to the scrubber. Therefore, normally electrostatic precipitators are applied, but baghouse filters can also be used.

The absorption of HCl takes place in a wet scrubber at an acidic pH value. Figure 13 gives an impression of a three-stage HCl scrubber. In the first step, the remaining dust particles, gaseous heavy metal salts, and some HCl is absorbed. Furthermore, the flue gas is cooled down to saturation temperature.

The main HCl absorption is carried out in two packed beds mounted one upon the other in the same column. Both beds are equipped with a separate circulation for the washing liquid. A countercurrent flow between the flue gas and the washing liquid is applied to realize a high concentration of HCl in the scrubbing solution. The product from the scrubber is a raw hydrochloric acid solution with about 15% HCl, which is further concentrated in downstream refining steps. The salt solution from the first quenching step has to be evaporated, e.g., together with the residues from acid refining, and the remaining solids are disposed of [47, 48].

2.2.3 Recovery of Gypsum

Because of the acidic pH value in the HCl scrubber, no absorption of sulfur dioxide takes place there. This happens in a second scrubber (cf. Fig. 14) with a higher pH value in the washing medium. To keep the pH value in the neutral region, the addition of a neutralization agent, normally limestone powder or hydrated lime, is necessary. If hydrated lime is used, the following chemical reaction takes place in the scrubber water:

$$SO_2 + Ca(OH)_2 \rightarrow CaSO_3\,½H_2O + ½H_2O$$

The emerging calcium sulfite can react to calcium hydrogen sulfite:

$$CaSO_3\,½H_2O + SO_2 + ½H_2O \rightarrow Ca(HSO_3)_2$$

And the hydrogen sulfite can be converted to gypsum by reacting with oxygen which may be present in the flue gas or is also injected into the scrubber sump (cf. Fig. 14):

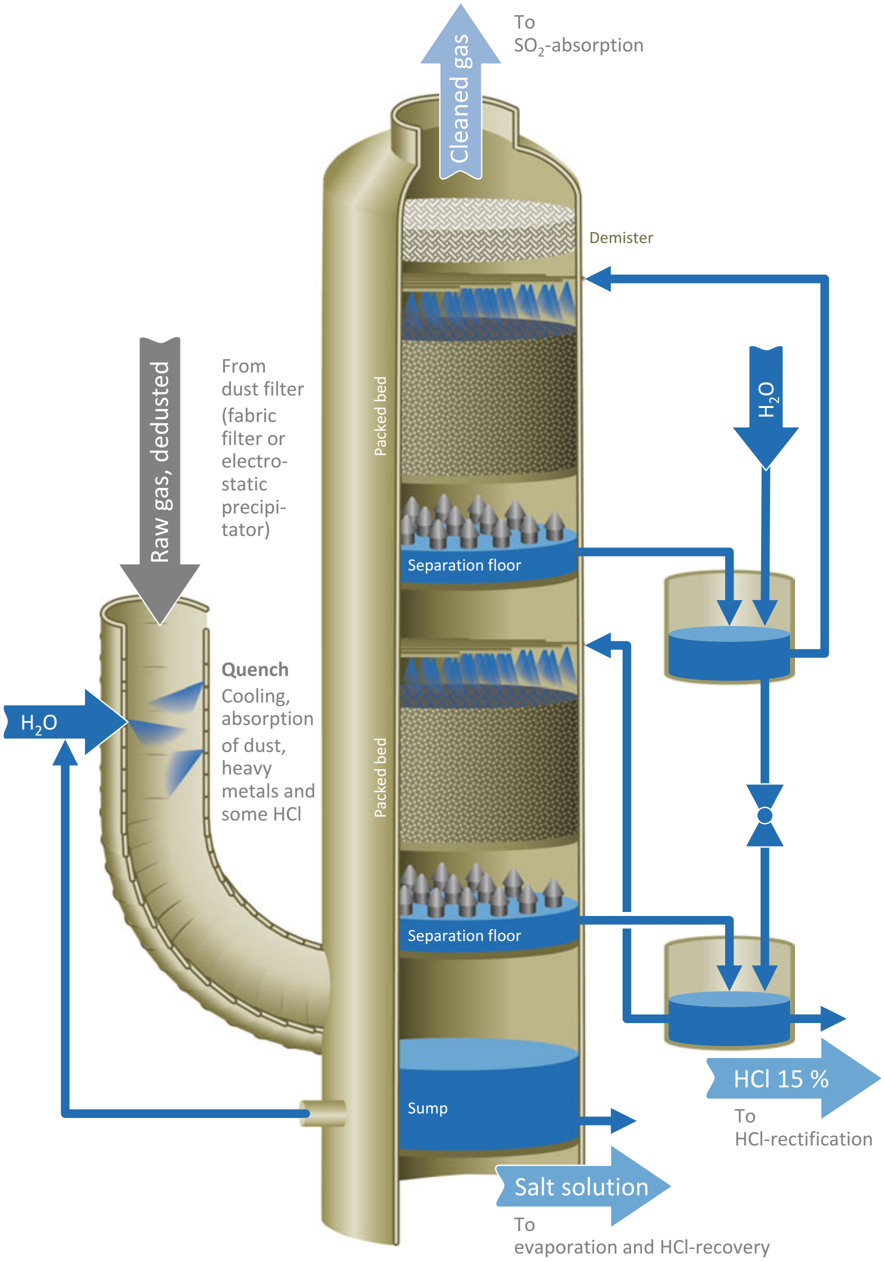

Fig. 13 Wet scrubbing system for three-step absorption of hydrochloric acid (HCl) from prior dedusted flue gas from MSWI (Graphic Peter Quicker, based on [47, 48])

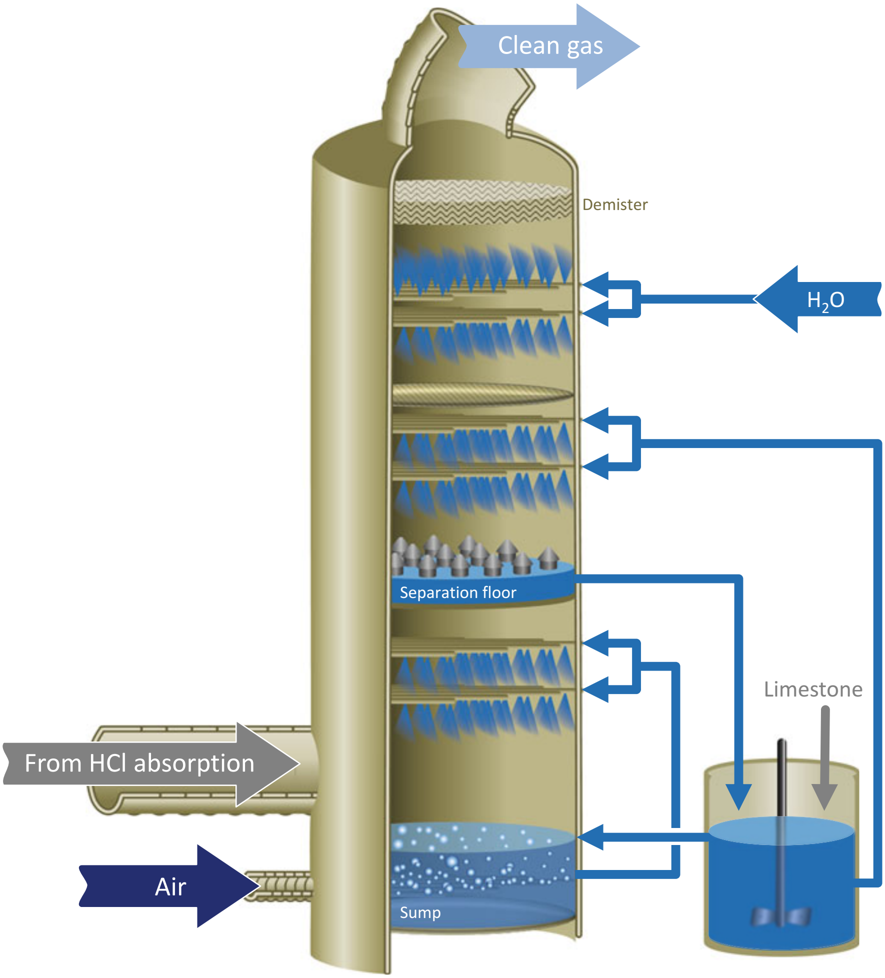

Fig. 14 Wet scrubbing system for absorption of sulfur dioxide (SO_2) from MSWI flue gas, before dedusting and cleaned from HCl (Graphic Peter Quicker, based on [47, 48])

$$Ca(HSO_3)_2 + \frac{1}{2}O_2 + H_2O \rightarrow CaSO_4\,2H_2O + SO_2$$

The direct oxidation of calcium sulfite to gypsum is also possible:

$$CaSO_3\,\frac{1}{2}H_2O + \frac{1}{2}O_2 + 1\frac{1}{2}H_2O \rightarrow CaSO_4\,2H_2O$$

2.2.4 Recovery of Zinc

An assumed typical dust concentration in the raw gas of MSWI plants of between 1 and 5 g/$m^3_{i.N.}$ (cf. Table 3) results in an annual amount of 1,100–5,500 tons of filter dust in a medium-sized MSWI plant[2] with a zinc content of about 50–250 tons. This potential provided motivation for the development of a new process for the recovery of zinc from the filter dust of a WtE plant that is operated at industrial scale in Solothurn, Switzerland. A scheme of this FLUREC process (German “FLUgasche RECycling,” i.e., fly ash recycling) is depicted in Fig. 15.

The new approach is based on the so-called FLUWA process (German FLUgasche WAesche), a fly ash scrubbing, which has been practiced for years in several Swiss WtE plants. The idea behind the FLUWA process is to extract leachable heavy metals from the filter ash by using the acid generated in the plant’s own scrubbing system. Simultaneously, the scrubbing water is neutralized by the alkaline components in the filter dust. The leached and dewatered filter dust can be landfilled. The heavy metals in the scrubbing solution are precipitated with milk of lime. The resulting hydroxide sludge can be used after dewatering for zinc recovery in a smelter due to its high zinc content (>25%) [28].

The FLUREC process goes one step further and includes all necessary processing steps – wet chemical processing and finally the electrolytic deposition of the metal – to recover metallic zinc from the hydroxide sludge directly in the WtE plant with a purity of 99.99%. As a by-product, a solid residue with a lead content of about 50% is generated that can also be used for metal recovery (in an external facility). It is planned to extend the capacity of the plant in the future to treat the filter dust from all MSWI plants in Switzerland [45].

3 Material Recovery by Pyrolysis

Thermochemical conversion in the absence of oxygen offers the chance for material recovery from special waste fractions containing valuables which are embedded in a matrix of volatile matter, like plastic. These may be composite material parts, like carbon fiber-reinforced plastics (CFRP), or metal-enriched fractions from (mechanical) upstream waste treatment processes like shredder residues. The plastics contained are volatilized at higher temperatures, and the emerging pyrolysis gases can be utilized to supply the thermal energy for the process by **direct** combustion. It is emphasized that a condensation and material utilization of the pyrolysis liquids as well as of the gases is not recommended due to their difficult processing and poor properties.

[2] Assumptions: 200,000 tons of waste throughput, specific flue gas amount of 5,500 $m^3_{i.N.}$/ton of waste.

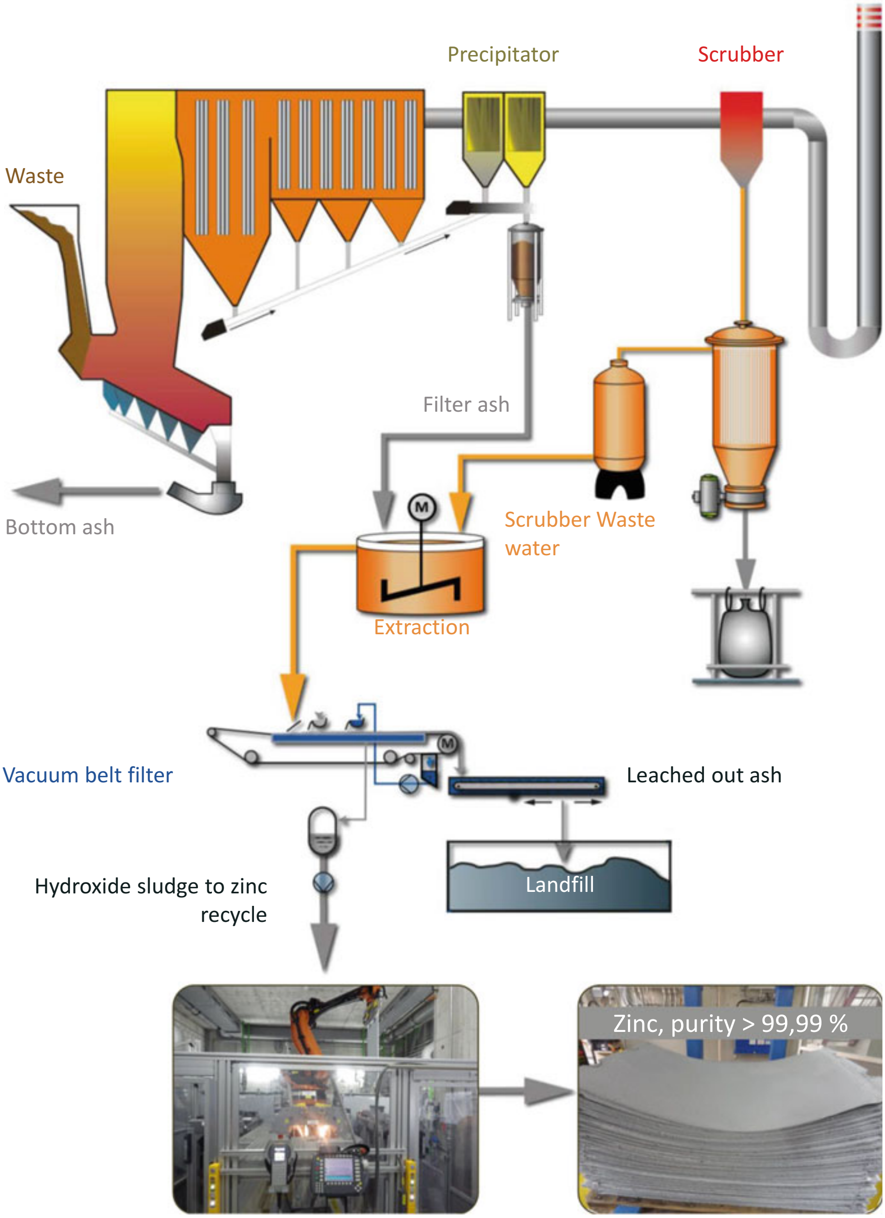

Fig. 15 FLUREC process for zinc recycling from WtE flue gas residues [28, 45]

The solid valuables remaining after pyrolytic treatment, e.g., metals, carbon fibers, etc., may have a high quality due to the inert atmosphere during treatment in the absence of oxygen. In the following, examples of the recovery of valuables from composite waste fractions by pyrolysis are given. The investigations were carried out by the Unit of Technology of Fuels at RWTH Aachen University.

3.1 Metals from Waste of Electrical and Electronic Equipment

The objective of the investigations was the realization of high metal recovery rates from the waste of electrical and electronic equipment (WEEE) with minimized effort for additional mechanical treatment by the application of a pyrolysis step. Ferrous and nonferrous metals were the designated fractions for recovery. The composite materials were treated in a rotary kiln at 600°C in an inert atmosphere. The gaseous, liquid, and solid products were sampled and analyzed. The single steps of the material processing are depicted in Fig. 16, and detailed information can be found elsewhere [49].

The consumer electronic devices for the test runs were obtained from a local WEEE collection point in the city of Aachen. The material was shred and the composition of the material was analyzed using manual sorting:

- 12.4 wt.-% metal-plastic composites with printed circuit boards
- 23.6 wt.-% metal-plastic composites without printed circuit boards
- 47.0 wt.-% free plastics
- 10.1 wt.-% free ferrous metals
- 1.9 wt.-% free nonferrous metals
- 5.1 wt.-% fines

The high amount of plastics in the material resulted in a significant content of 49 wt.-% volatile components and an average calorific value of 24.7 MJ/kg.

After manual analysis, the material was mixed again and treated as shown in Fig. 16 by magnet and eddy current separation to enrich the metal composites prior to thermal decomposition. The pyrolysis was carried out in an electrically heated laboratory-scale rotary kiln reactor (drum diameter 162 mm, length 1,600 mm). Residence time of the solids in the reactor was between 30 and 60 min. The condensable components in the pyrolysis gas were collected in liquid form, and the volume and composition of the remaining permanent gases were measured before the gas was incinerated with a burner. The solids were screened after the thermal treatment to separate the fines, predominantly coke, from the metals.

The amount of condensates and noncondensable gases varied greatly from 5 to 10 and 1 to 10 wt.-%, respectively. The gas predominantly contained combustible components, i.e., hydrogen, carbon monoxide, methane, ethane, ethylene, and other organic hydrocarbons, but inert gases such as nitrogen and carbon dioxide were also detected.

The composition of the solid products (red columns) as well as of the input material (blue columns) for the pyrolysis step is shown in Fig. 17 (Fe-concentrate

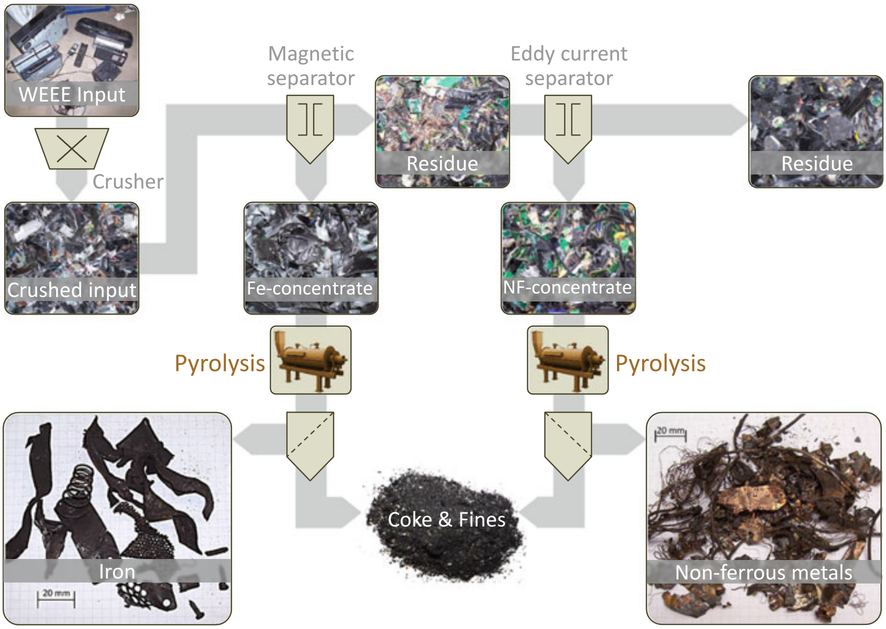

Fig. 16 Thermomechanical processing of waste of electrical and electronic equipment (WEEE) for recovery of iron and nonferrous metals (NF = nonferrous)

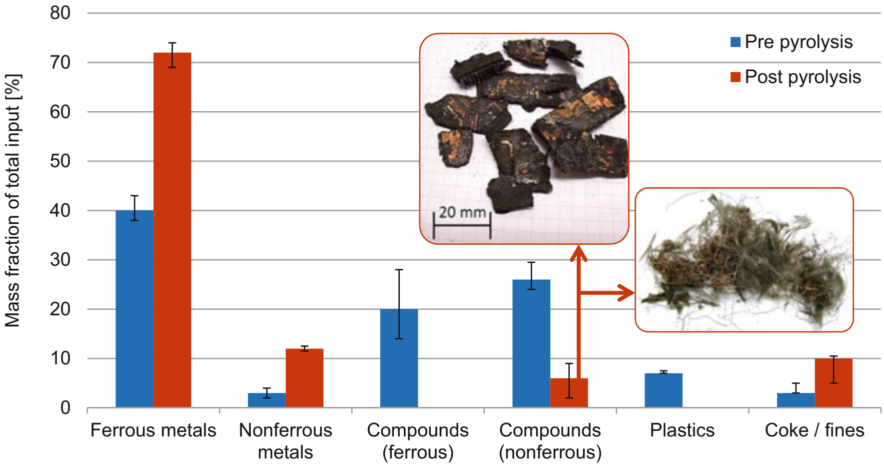

Fig. 17 Composition of solid residues after common pyrolysis of ferrous and nonferrous concentrates from mechanical processing of WEEE

and NF-concentrate together, mean values of four trials). It is clearly visible that the share of free metals (iron and nonferrous metals) could be significantly increased using the pyrolytic treatment. In the case of iron, all composites could be totally destroyed, and only free iron with no adhesions could be found in the product. Also, the amount of nonferrous composites could be reduced. However, after all trials, nonferrous metal composites were still detected in the product. These composites primarily consisted of copper from printed circuit boards, which was interwoven with a glass fiber matrix (cf. photos in Fig. 17). The coke contained high amounts of chlorine up to 5 wt.-%, caused by the plastics (PVC) in the input material.

The concept was also successfully tested for other metal concentrates, e.g., for fractions from auto shredders or ferrous metal-enriched fractions from the processing of landfill material [49].

3.2 Carbon Fiber-Reinforced Plastics

Composite materials offer interesting properties, like high mechanical and chemical stability at a low weight. In particular, fiber-reinforced plastics are an increasing market segment and present in a multitude of different branches, like aerospace, defense, power generation (windmills), but also sports and leisure. Whereas the market is actually dominated by glass fiber-reinforced plastics, carbon fibers are a steadily growing segment. In 2016, about 46,000 tons of carbon fibers and 100,000 tons of CFRP were produced globally [50].

CFRP are composite materials with carbon fibers that are embedded in a polymer matrix. The production is very complex and energy intensive, resulting in production costs of 20–100 €/kg. This makes the recycling of these materials – that means the recovery of clean fibers to use with a new matrix for the production of new composites – economically very interesting. However, the recycling of CFRP is a challenge.

To separate the fibers from a thermoset matrix, the matrix had to be decomposed completely without any damage of the fibers. Solvolysis (chemical disintegration) and pyrolysis are possible processes for this purpose.

To carry out a solvolysis, the composition of the matrix should be known. Only on this basis can a functional and efficient process, with recovery and reuse of matrix and solvent, be developed. Unfortunately, the matrix material is normally unknown and not disclosed by the production companies because of confidentiality reasons. This presumably limits solvolytic approaches to in-house solutions for production residues.

Pyrolysis processes, on the other hand, can be operated totally independent from the knowledge of the matrix material. The arising pyrolysis gases can be incinerated and the energy be used for heating the process.

A pyrolysis-specific disadvantage is the formation of a solid carbon residue from the polymer decomposition. This char attaches to the fibers in brittle deposits (see Fig. 18, left picture). Fibers with deposits cannot be sized and reintegrated into a polymer matrix, and therefore not be reused at all. In fact, the char can be removed by an additional thermal treatment in the presence of oxygen, as depicted in the middle (5 min. of oxidation) and right picture (20 min. of oxidation) of Fig. 18. This, however, may damage the fibers and can reduce their tensile strength [51, 52].

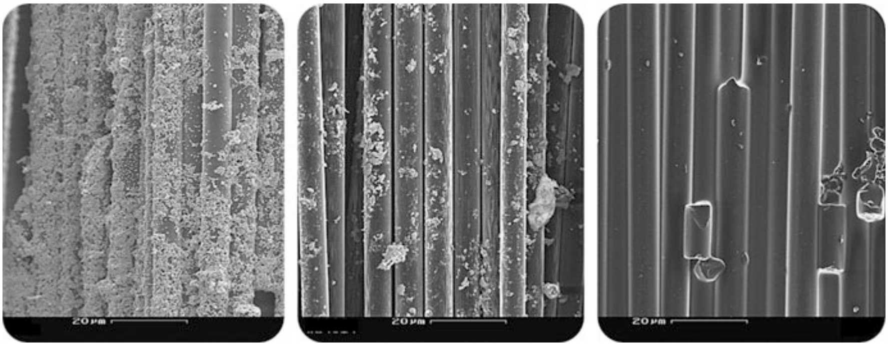

Fig. 18 SEM micrograph pictures of carbon fiber-reinforced plastics (CFRP) samples (dry fiber), treated at 670°C for 20 min in inert atmosphere (*left*). *Middle picture*: after pyrolysis an additional oxidation step (ambient air) was applied for 5 min. *Right*: oxidation step was extended to 20 min

If the fibers are exposed to an oxygen-containing atmosphere for longer, they may be totally destroyed and form small fragments of a needle shaped structure (Fig. 19). The resulting fiber dimensions and shapes can reach WHO criteria for being potentially harmful to humans.

4 Summary and Conclusion

The subject of this text is the recovery of materials in the course of the thermal treatment of waste. Even if thermal treatment is supposed to destroy materials, it offers good opportunities to recover thermostable substances, like metals and minerals.

Residues from MSWI include bottom ash and the products and deposits from flue gas cleaning.

The recovery of metals from bottom ash has a long tradition and reached a very high technical level within the last few years. Today even nonferrous metals can be recovered with high efficiency. Nevertheless, research and development is still going on in the field to optimize the metal yield and quality. Contrary to the metal components in the bottom ash, it is difficult to find reasonable recycling possibilities for the mineral fraction in most regions because natural building materials are often available, they are inexpensive, and do not have the “smell of waste.”

Also from the flue gas of the incinerators, a recovery of materials is possible. Traditionally HCl and gypsum can be recovered from the flue gas scrubbers. Unfortunately, the acceptance of these products is not very high because of the origin of the materials in the waste business. In Switzerland, new approaches to recover metals, predominantly zinc and lead from the filter dust of the plants, have been developed and are implemented on an industrial scale.

Besides waste incineration, the thermochemical conversion by pyrolysis also offers interesting technical opportunities for waste treatment and material recovery.

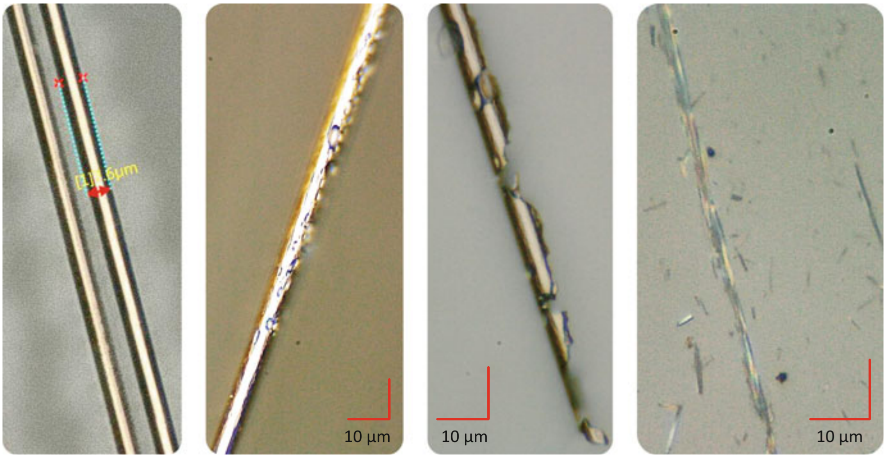

Fig. 19 Optical microscope pictures of carbon fibers, thermally treated at different temperatures and residence times (additionally to the time for heating up the sample) under ambient air atmosphere. From *left to right*: 700°C, 10 min – 800°C, 10 min – 900°C, 10 min – 900°C, ca. 40 min

Modern products and pre-concentrates from waste treatment facilities are often composed of different substances, components, and materials, e.g., WEEE, fiber-reinforced plastics, shredder fractions, etc., which cannot be separated by mechanical methods only. On the other hand, the incineration of the combustible part of the materials may damage some of the valuable components (e.g., carbon fibers and metals) in the composite materials. For these fractions, a pyrolytic treatment at relatively low temperatures and in the absence of oxygen may be the right processing step. Volatile plastic components can be easily removed, and the valuables in the materials are not negatively affected and can be recovered with high quality.

It is especially emphasized that the recovery of fuels or high-grade chemicals from MSW by thermochemical processes is not a reasonable pathway for the treatment of these fractions. Despite great efforts in the past, no economically feasible process for this purpose could show its practicability on an industrial scale and in a longtime operation.

References

1. Quicker P, Neuerburg F, Noël Y, Huras A (2017) Sachstand zu den alternativen Verfahren für die thermische Entsorgung von Abfällen. In: Umweltbundesamt (ed) TEXTE. Download https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2017-03-06_texte_17-2017_alternative-thermische-verfahren.pdf
2. Quicker P, Stockschläder J (2016) Möglichkeiten einer ressourcenschonenden Kreislaufwirtschaft durch weitergehende Gewinnung von Rohstoffen aus festen Verbrennungsrückständen aus der Behandlung von Siedlungsabfällen. Abschlussbericht zum Vorhaben UBA-FB 3713 33 303des Umweltforschungsplans des Bundesministeriums für Umwelt, Naturschutz, Bau und Reaktorsicherheit
3. Verein Deutscher Ingenieure (ed) (2014) VDI 3460 emission control – thermal treatment of waste. Beuth Verlag, Düsseldorf
4. De Fodor A (1989) Elektrizität aus Kehricht. Budapest (1911). In: MABEG, Gesellschaft für Abfallwirtschaft und Entsorgung (ed) Nachdruck der Originalausgabe
5. Thomé-Kozmiensky KJ, Pahl U (eds) (1994) Thermische Abfallbehandlung. 2. Auflage. Berlin
6. Statistisches Bundesamt (ed) (2016) Abfallbilanz 2014. Wiesbaden. Download https://www.destatis.de/DE/Publikationen/Thematisch/UmweltstatistischeErhebungen/Abfallwirtschaft/AbfallbilanzPDF_5321001.pdf?__blob=publicationFile
7. Martens H (2016) Recyclingtechnik. Springer Fachmedien, Wiesbaden
8. Kuchta K, Enzner V (2015) Endbericht Metallrückgewinnung aus Rostaschen aus Abfallverbrennungsanlagen – Bewertung der Ressourceneffizienz. Entsorgergemeinschaft der Deutschen Entsorgungswirtschaft e.V. Download http://www.entsorgergemeinschaft.de/index.php?id=154
9. Adam F, Böni D, Böni F (2011) Technischer Statusbericht Thermo-Recycling. Stiftung Zentrum für nachhaltige Abfall- und Ressourcennutzung. Hinwil. Download https://zar-ch.ch/fileadmin/user_upload/Contentdokumente/Oeffentliche_Dokumente/zar_technischerzwischenbericht.pdf
10. Böni D (2010) Ausbeute aus der Trockenschlacke. VDI Wissensforum Feuerung und Kessel – Beläge und Korrosion in Großfeuerungsanlagen. Frankfurt. Download https://zar-ch.ch/fileadmin/user_upload/Contentdokumente/Oeffentliche_Dokumente/Ausbeute__aus_Trockenschlacke.pdf
11. Lamers F (2015) Treatment of bottom ashes of waste-to-energy installations – state of the art. In: Thomé-Kozmiensky KJ, Thiel S (eds) Waste management, Waste-to-energy, vol 5. TK Verlag Karl Thomé-Kozmiensky, Neuruppin, pp 271–292
12. Wieduwilt M, Müller R, Luzzatto M, Brison A (2015) Advanced Urban Mining: a summary of the state of the art of metal recovery out of dry bottom ash. In: Thomé-Kozmiensky KJ, Thiel S (eds) Waste Management, Waste-to-energy, vol 5. TK Verlag Karl Thomé-Kozmiensky, Neuruppin, pp 293–304
13. Eckert S (2016) Modernisierung der Ofenlinie 2 der KVA Horgen und Umbau auf Trockenschlackenaustrag. Vortrag Informationsveranstaltung ZAR. Download https://zar-ch.ch/fileadmin/user_upload/Contentdokumente/Veranstaltungen/Info_2016/ZARInfo16_Eckert_S_ZAR_Tockenaustrag_KVA_Horgen_HZI.pdf
14. Fleck E, Langhein E-C, Blatter E (2013) Metallrückgewinnung aus trocken ausgetragenen MVA-Schlacken. In: Thomé-Kozmiensky KJ (ed) Aschen, Schlacken, Stäube. TK Verlag Karl Thomé-Kozmiensky, Neuruppin, pp 323–339
15. Gablinger H, Juchli M (2016) KEBAG-Trockenschlackeaustrag für Feinschlacke. Vortrag Informationsveranstaltung ZAR. Download https://zar-ch.ch/fileadmin/user_upload/Contentdokumente/Veranstaltungen/Info_2016/ZARInfo16_DrGablinger_H_Juchli_M_Grate_for_Riddlings.pdf
16. Hitachi Zosen Inova HZI (2016) Nass- und Trockenaustrag von Rostasche? HZIs Grate for Riddlings kombiniert beides. Meldung RecyclingPortal. Download http://recyclingportal.eu/Archive/27826

17. Martin JJE, Koralewska R, Wohlleben A (2015) Advanced solutions in combustion-based WtE technologies. In: Special thematic issue: waste-to-energy processes and technologies, vol 37. Jg, pp 147–156
18. Bunge R (2016) Aufbereitung von Abfallverbrennungsaschen – Eine Übersicht. In: Thomé-Kozmiensky KJ (ed) Mineralische Nebenprodukte und Abfälle, vol 3. TK Verlag Karl Thomé-Kozmiensky, Neuruppin, pp 141–161
19. Bunge R (2010) Wertstoffgewinnung aus KVA-Rostasche. In: Schenk K (ed) KVA-Rückstände in der Schweiz. Bundesamt für Umwelt BAFU, Bern, pp 170–184
20. Deike R, Ebert D, Warnecke R, Vogell M (2012) Recyclingpotenziale bei Rückständen aus der Müllverbrennung. Abschlussbericht. Download https://www.itad.de/information/studien/20130110DEIKEH dasRecyclingpotentialAbschlussbericht.pdf
21. Kersting D (2013) Aufbereitung und Verwertung von MV-Schlacken. 25. VDI-Fachkonferenz Thermische Abfallbehandlung. VDI-/ITAD-Spezialtag: Aufbereitung und Verwertung von MVA-Schlacken. 9.-11. 2013 Würzburg
22. Lechner P, Mostbauer P (2010) Grundlagen für die Verwertung von MV-Rostasche. Teil B: Aufbereitungstechnik und Innovationen. Download https://www.bmlfuw.gv.at/dam/jcr:3e990e78-f77d-4d52-b9a1-b3b5ffe5630a/BOKU_Grundsatz_Teil_A_Rostasche.pdf
23. Meinfelder T, Richers U (2008) Entsorgung der Schlacke aus der thermischen Restabfallbehandlung. Wissenschaftliche Berichte, FZKA 7422
24. Ministerium für Umwelt und Naturschutz, Landwirtschaft und Verbraucherschutz und Ministeriums für Wirtschaft und Mittelstand, Energie und Verkehr NRW (2001) Anforderungen an den Einsatz von mineralischen Stoffen aus industriellen Prozessen im Straßen- und Erdbau. Gem. RdErl
25. Koralewska R (1999) Naßchemische Behandlung von Rostschlacken aus MVA. Dissertation der TU München. In: Berichte aus Wassergüte- und Abfallwirtschaft, vol 151. München
26. Lück T (2004) Verfahren der Scherer + Kohl GmbH zur weitergehenden Schlackeaufbereitung. In: Thomé-Kozmiensky KJ (ed) Optimierung der Abfallverbrennung 1. TK Verlag Karl Thomé-Kozmiensky, Neuruppin, pp 621–643
27. Länderarbeitsgemeinschaft Abfall (LAGA) (2003) Mitteilung 20 Anforderungen an die stoffliche Verwertung von mineralischen Reststoffen/Abfällen – Technische Regeln. Stand
28. Thomé-Kozmiensky KJ (2013) Möglichkeiten und Grenzen der Verwertung von Sekundärabfällen aus der Abfallverbrennung. In: Thomé-Kozmiensky KJ (ed) Aschen – Schlacken – Stäube aus Metallurgie und Abfallverbrennung. TK Verlag Karl Thomé-Kozmiensky, Neuruppin, pp 77–278
29. Berkhout P, Rem P (2015) Separation apparatus, United States patent US 9,033,157
30. Van de Weijer R. Optimisation of bottom ash treatment. Download http://www.aebamsterdam.nl/media/1323/04-presen-tatie-bodemas.pdf
31. de Vries W, Rem P, Berkhout M (2014) ADR – a new method for dry classification. In: Thomé-Kozmiensky KJ, Thiel S (eds) Waste-to-energy, Waste management, vol 4. TK Verlag, Neuruppin, pp 331–344
32. Holm O (2014) r^3 Verbundprojekt ATR. Essen
33. Holm O (2015) r^3 Verbundprojekt ATR. Bonn
34. Lübben S (2015) Treatment of bottom ash, metal recovery and recycling of minerals. Hamburg
35. Simon F-G, Holm O (2013) Aufschluss, Trennung und Rückgewinnung von Metallen aus Rückständen thermischer Prozesse. Verdoppelung der Metallausbeute aus MVA-Rostasche. In: Thomé-Kozmiensky KJ (ed) Aschen, Schlacken, Stäube. TK Verlag, Neuruppin
36. Rüßmann D, Pretz T (2015) Verlustminimiertes Metallrecycling aus Müllverbrennungsaschen durch sen-sorgestützte Sortierung – VeMRec, TP 6 Aufbereitung: BMBF-Förderprogramm r^3 – Innovative Technologien für Ressourceneffizienz – Strategische Metalle und Mineralien: Urban Mining – Rückgewinnung von Wertstoffen aus anthropogenen Lagern, Gewinnung von Wertstoffen aus dem Rückbau von Altdeponien und Hüttenhalden sowie aus Verbrennungsrückständen": Schlussbericht zu dem vom BMBF geförderten Verbundprojekt. Laufzeit: 01.05.2012–31.04.2015

37. Breitenstein B, Goldmann D (2013) ReNe-Verfahren zur Rückgewinnung von dissipativ verteilten Metallen aus Verbrennungsrückständen der thermischen Abfallbehandlung. In: Thomé-Kozmiensky KJ (ed) Aschen, Schlacken, Stäube. TK Verlag, Neuruppin, pp 341–352
38. Breitenstein B, Goldmann D (2015) NE-Metallrückgewinnung aus Abfallverbrennungsschlacken unterschiedlicher Herkunft. In: Thomé-Kozmiensky KJ (ed) Mineralische Nebenprodukte und Abfälle 2. TK Verlag, Neuruppin, pp 255–270
39. Knorr W, Hentschel B (1999) Rückstände aus der Müllverbrennung. Chancen für eine stoffliche Verwertung von Aschen und Schlacken. In: Initiativen zum Umweltschutz, vol 13. Berlin
40. Koralewska R (2013) Verfahren zur Inertisierung von Aschen/Schlacken aus der Rostfeuerung. In: Thomé-Kozmiensky KJ (ed) Aschen – Schlacken – Stäube – aus Abfallverbrennung und Metallurgie. TK Verlag, Neuruppin
41. Lübben S (2015) Verwertung von Abfallverbrennungsasche als Zuschlagsstoff in der Beton-, Asphalt- und Zement-industrie. In: Thomé-Kozmiensky KJ (ed) Mineralische Nebenprodukte und Abfälle 2. TK Verlag, Neuruppin, pp 321–335
42. Ardia P, Böni D, Büchi U, Di Lorenzo F, Schlumberger S (2014) Geschäftsbericht/Tätigkeitsbericht 2014. Download http://zar-ch.ch/fileadmin/user_upload/Contentdokumente/Oeffentliche_Dokumente/ZAR_GB_2014_DE.pdf
43. Franz M (2014) KVA – Schlackenaufbereitung in der Schweiz. Von den Anfängen bis heute. Download http://www.nutecag.ch/home/images/Nutec/downloads/Schlacke.pdf
44. IGENASS. Interessengemeinschaft Nassaustrag. www.igenass.ch
45. Schlumberger S, Bühler J (2013) Metallrückgewinnung aus Filterstäuben der thermischen Abfallbehandlung nach dem FLUREC-Verfahren. In: Thomé-Kozmiensky KJ (ed) Aschen – Schlacken – Stäube – aus Abfallverbrennung und Metallurgie. TK Verlag Karl Thomé-Kozmiensky, Neuruppin, pp 377–398. Download http://www.vivis.de/phocadownload/2013_ass/2013_ass_377_398_schlumberger.pdf
46. Karpf R (2016) Aktueller Stand der Abgasreinigung bei der thermischen Abfallbehandlung. In: Quicker P, Schnurer H, Zeschmar-Lahl B (eds) Müll-Handbuch. Erich Schmidt Verlag, Berlin
47. Sattler K (2012) Thermische Trennverfahren: Grundlagen, Auslegung, Apparate. Wiley, Weinheim
48. Schönbucher A (2002) Thermische Verfahrenstechnik: Grundlagen und Berechnungsmethoden für Ausrüstungen und Prozesse. Springer Verlag, Berlin Heidelberg
49. Rotheut M, Horst T, Quicker P (2015) Thermomechanical treatment of metal composite fractions. Chem Ing Tech 87(11):1504–1513
50. Kraus T, Kühnel M, Witten E (2016) Composites-Marktbericht. Download http://www.avk-tv.de/files/20161128_marktbericht_2016deutsch.pdf
51. Limburg M, Quicker P (2016) Entsorgung von Carbonfasern – Probleme des Recyclings und Auswirkungen auf die Abfallverbrennung. In: Thomé-Kozmiensky KJ, Beckmann M (eds) Energie aus Abfall, vol 13. TK Verlag Karl Thomé-Kozmiensky, Neuruppin
52. Limburg M, Quicker P (2016) Disposal of carbon fibre reinforced polymers. In: Thomé-Kozmiensky KJ, Thiel S (eds) Waste Management, Waste-to-energy, vol 6. TK Verlag Karl Thomé-Kozmiensky, Neuruppin

Source-Separated Collection of Rural Solid Waste in China

Chao Zeng, Hangfen Li, Fafa Xia, Dongjie Niu, and Youcai Zhao

Abstract The rapid urbanization progress and the continuous improvement of rural residents' living standards are contributing to the increase in rural solid waste (RSW) in China. RSW generation rates range from 0.25 to 2.3 kg (capita d)$^{-1}$ in different rural areas, and the real total RSW generation amount was far higher than official data in 2014. RSW is dominated by food residue and coal ash/cinder/dust in rural China, and most of it is discarded randomly without any treatment. In this work, rural household behaviors toward RSW treatment and their perceptions in terms of awareness and attitudes on the source-separated collection of RSW are investigated with a questionnaire survey consisting of 518 valid samples. The results indicated that some rural households had spontaneously separated the recyclable waste and food waste to some extent. The public were aware of the importance of RSW separation through various media, and more than half of households were willing to participate in a separation program. The dominant barriers to participation were the lack of awareness of separation, inconvenience, and an insufficient separation facility (53.7%). 62.5% of rural households had a positive willingness to pay (WTP) for RSW separation and management, and the mean WTP was estimated to be 3.8 USD/year. Age, annual household income, and location significantly influenced the respondents' WTP. More positive policy is necessary to encourage the local government to devote efforts to provide collection service and improve RSW management by combining the governmental financial budget and rural household payments.

Keywords Characteristics, China, Informal sector recycling, Management, Public opinion, Rural solid waste, Source-separated collection

C. Zeng, H. Li, F. Xia, D. Niu, and Y. Zhao (✉)
State Key Laboratory of Pollution Control and Resource Reuse, School of Environmental Science and Engineering, Tongji University, Shanghai 200092, China
e-mail: zhaoyoucai@tongji.edu.cn

R. Maletz et al. (eds.), *Source Separation and Recycling*,
Hdb Env Chem (2018) 63: 151–174, DOI 10.1007/698_2017_30,

© Springer International Publishing AG 2017, Published online: 3 June 2017

Contents

1 Introduction

As the largest developing country with the highest population in the world, China has achieved immense achievements in terms of economic growth and urbanization process from the late 1970s to date but meanwhile has paid a heavy price in the environment and ecology. It is well known that China has devoted extensive efforts to environmental protection in recent years. Yet the former research and policies on environmental protection preferentially focused on industry and urban pollution control instead of rural areas. Currently, with the rapid development of the rural economy and social transformation, rural China is also faced with multiple environmental problems, and one of the increasingly serious consequences is rural solid waste (RSW) [1].

As is known to all, little attention has been paid to RSW in most developing countries. As a fast-developing country and the largest municipal solid waste (MSW) generator in the world, China is no exception. In earlier times, a considerable amount of RSW (especially the organic wastes) was recycled as food for livestock or fertilizer for agriculture. However, the ever-accelerating urbanization progress and the continuous improvement in rural residents' living standards contributed to the rapid increase in RSW generation. Nevertheless, the Chinese government faces great difficulties in providing RSW management services in rural China. Generally, for those rural areas in developed regions, RSW was first collected in the village and then transported to transfer stations situated in towns or the county for downstream treatment and disposal. This mode is restricted by the cost of waste transportation in those remote rural areas. Consequently, RSW management has become a challenge to local governments.

Rural areas account for 90% of mainland China, which consist of towns and villages, the two smallest administrative levels in China under nation, province, prefecture/municipality, and county. There were 642 million people (about 47.43% of the Chinese population) in rural areas in 2012. The current social and economic backgrounds of the typical rural areas in different cities or provinces vary greatly. It is reported that the per capita net annual income varied from 652.6 to 2,578.4 USD in 2012. As mentioned before, MSW management is only practiced in cities, while RSW management is at best only partially established in some developed rural areas.

Worldwide experiences show that the source-separated collection of solid household waste is an effective method for the enhancement of waste reduction and recycling [2, 3]. It has been widely used in developed countries for the purpose of sustainable development. In 2000, a pilot program focusing on the source-separated collection of MSW was launched in eight major cities throughout China, and some successful experiences were accumulated [4]. As a key component of an integrated waste management system, it is necessary for rural households to separate RSW at the source. The source-separated collection of RSW cannot only reduce the transportation costs but also contribute to recycling waste and diverting part of the RSW from the dumping sites. However, it has not been applied broadly in rural China, with merely some pilot projects in single villages reported in casebooks or newspapers. However, it can be predicted that the source-separated collection of RSW in China is promising in the next 5 years [5].

2 RSW Generation and Composition

RSW consists mainly of organic wastes, including food and kitchen waste, and recyclable wastes including papers, plastics, glasses, metals, textiles, and leather. The nonrecyclable wastes include slag and its by-products and other hazardous wastes. Special rural waste streams, such as solid wastes produced in rural industries and agricultural and forestry waste, are beyond its scope.

2.1 RSW Generation

According to the *National Rural Environmental Pollution Prevention Planning Outline (2007–2020)*, the annual total amount of RSW generation is approximately 280 million tons. However, the newest authoritative data declared by the Ministry of Housing and Urban-Rural Development (MOHURD) of the People's Republic of China in *People's Daily*, the government's official newspaper in China, is approximately 110 million tons, which shows a distinct divergence in annual RSW generation. Some researchers conducted a field survey to explore this issue themselves, whereas most data are based on small-scale surveys or just simple case studies of pilot projects. Some estimated results based on the rather incomplete statistics in different studies vary widely, e.g., with estimated generation of 140 million tons in 2000 [6], 180 million tons in 2005 [7], and 236 million tons in 2010 [1]. This is mostly because some differences may exist with the survey errors and statistical method. Despite some uncertainties in these results, it still reveals an increasing trend in the total amount of RSW generation. Otherwise, the RSW generation rate in nationwide rural areas also varies in different literatures, e.g., with estimated rates of about 1.34 kg (capita d)$^{-1}$ in 2003 [8], 0.9 kg (capita d)$^{-1}$ in 2006 [9], and 0.95 kg (capita d)$^{-1}$ in 2010 [1].

Table 1 presents RSW generation rates across regions of China [10], showing that most data are less than 1 kg (capita d)$^{-1}$. Similar to the estimate of RSW generation, the RSW generation rate also shows an increasing trend. It varies significantly among different rural villages across regions of China (ranging from 0.15 to 2.22 kg (capita d)$^{-1}$) and sometimes even in the same region (e.g., Beijing, Jiangsu, and Zhejiang province, respectively). In general, it implies that the rate in northern China is higher than that of southern China, and the rate in eastern China is higher than that of western China, and this result is consistent with the previous study. Several factors may account for this phenomenon: rural population and its distribution, income level, dietary habits, consumption level, etc., which are similar to the main factors that influence the MSW generation rate in China.

2.2 RSW Composition

Table 2 presents a comparison of the physical composition of RSW in various cities or provinces in China [10]. On the one hand, the proportion of RSW compositions differs dramatically, owing to differences in climate, dietary habits, culture, season, and living standards. Besides, as was reported, RSW composition (No. 6–8) was similar to MSW composition in some relatively developed rural areas of eastern China, inferring that urban lifestyle could influence surrounding rural villages. On the other hand, food residue and miscellaneous inorganic wastes, regarding coal ash, slag, and dust as well as plant ash, are the two major components of RSW. It is noticeable that waste composition in northern China is dominated by high inorganic content, achieving the highest proportion at approximately 70%. These wastes probably originate from household fuel because of heating in the cold season or the preparation and cooking of food. However, there would be a reduction in ash/soil residue content in the future, as coal will be replaced by natural gas or rural biogas [11, 12]. Besides, RSW composition in most villages in eastern China and southern China is dominated by a high proportion of organic content in terms of food residue. It can be considered that food residue will still continue to be the main component in rural China in the future. In addition to organic waste and inorganic

Table 1 Summary of the RSW generation rate in China

No.[a]	Location	Year	Survey method	Generation rate/kg $(capita\ d)^{-1}$
1	Beijing 1	2006	Household survey	1.5–2.1
2	Beijing 2	2010	Questionnaire	1.46
3	Shenyang, Liaoning province	2005	Household survey	0.66–2.33
4	Jilin province	2010	Questionnaire	1.25
5	Hebei province	2010	Questionnaire	1.13
6	Yixing, Jiangsu province	2002–2005	Household survey	0.15–0.30
7	Nantong, Jiangsu province	2007	Household survey	0.69
8	Fujian province	2006	Questionnaire	0.73
9	Zhejiang province 1	2006	Questionnaire	1
10	Zhejiang province 2	2008	Household survey	0.48
11	Zhejiang province 3	2010	Questionnaire	0.83
12	Chongqing	2008	Household survey	0.21–0.43
13	Anhui province	2010	Questionnaire	0.75
14	Sichuan province	2010	Questionnaire	0.73
15	Yunnan province	2010	Questionnaire	0.58
16	Guangzhou, Guangdong province	2012	Questionnaire	0.82
17	Dongguan, Guangdong province	2012	Questionnaire	0.75
18	Zhongshan, Guangdong province	2012	Questionnaire	0.58

[a]No. 1–5 belong to northern China, No. 6–11 belong to eastern China, No. 12–18 belong to southern China

waste, there is a certain amount of recyclable waste, indicating a trend of urbanization and economic development.

2.3 *Comparison of Characteristics Between RSW and MSW in China*

Figure 1 presents a brief comparison of generation rates between RSW and MSW in China. Surveyed RSW data are selected in Table 1, with the corresponding MSW data of their administrative city or province in 2008 obtained in the literature [13]. It is clear that most MSW generation rates are substantially higher than in their

Table 2 Comparison of typical RSW compositions in different regions across China/wt. %

No.[a]	Location	Year	Food residue	Plant ash	Coal ash, cinder, dust	Paper	Plastic	Glass	Metal	Textiles	Wood	Hazardous waste
1	Beijing 1	2006	26.28	–	58.97	3.94	5.48	0.9	0.16	1.16	3.05	–
2	Beijing 2	2013	36.84	–	35.43	4.2	12.81	2.69	1.33	5.76	0.95	–
3	Shenyang 1, Liaoning province	2005	4.43	25.46	68.57	0.08	0.14	0.97	0.03	0.13	0.19	–
4	Shenyang 2, Liaoning province	2005	81.25	–	–	4.92	8.71	0.27	2.62	1.13	1.1	–
5	Yixing, Jiangsu province	2004	62.7	–	8.9	4.1	21.2	0.8	0.1	2.2	–	–
6	Danyang, Jiangsu province	2006	30.9	–	47.68	2.21	1.52	2.44	0.42	2.59	9.39	–
7	Nantong, Jiangsu province	2007	49.4	–	29.1	3.3	8.6	2.4	2.2	3.8	–	1.3
8	Zhejiang province	2006	69	–	–	9	15	4	1	–	–	–
9	Yunnan province	2012	55.07	–	15.91	8.37	8.28[b]	1.55	0.1	0.37	9.26	–
10	Macheng, Hubei province	2013	12.38	–	53.09	6.73	15.16	3.54	1.56	4.52	2.84	0.38

[a]No. 1–4 belong to northern China, No. 5–8 belong to eastern China, No. 9–10 belong to southern China
[b]8.28 represents rubber here

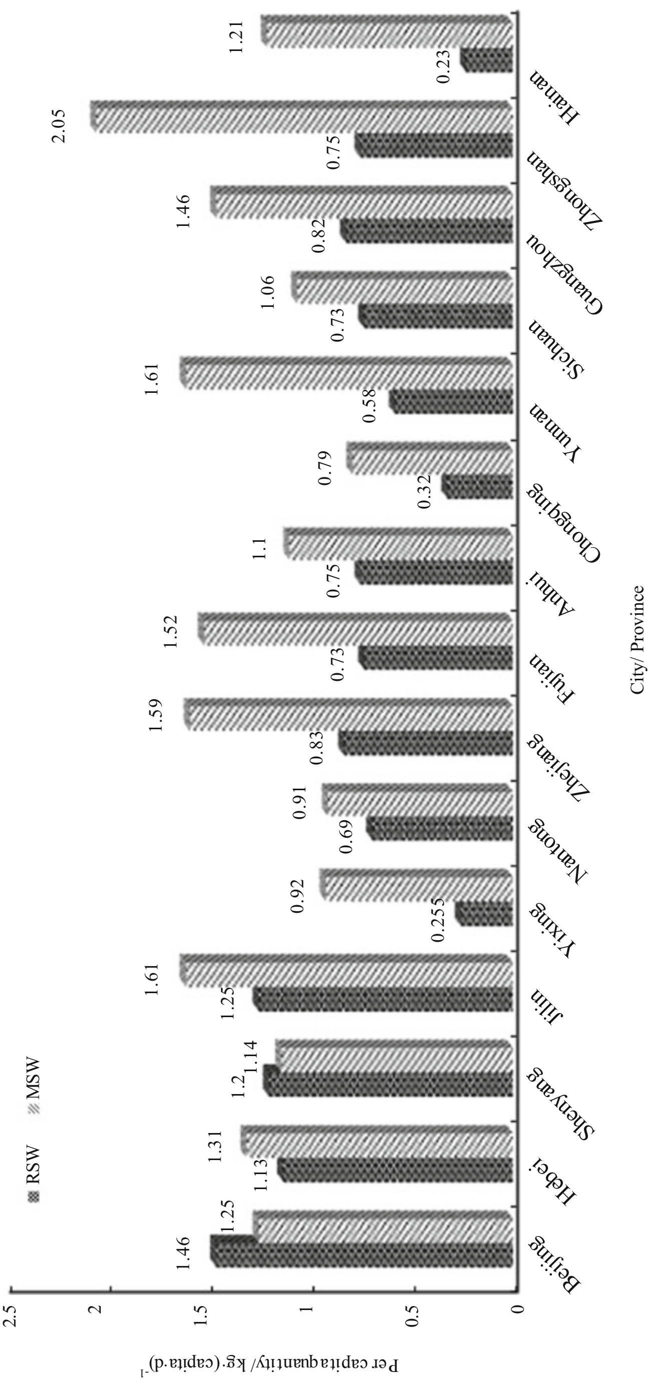

Fig. 1 Comparison of the generation rates between RSW and MSW in China

corresponding rural areas except for the provinces of Beijing, Shenyang, and Hebei. There is a possibility that official MSW data is slightly lower than the reality, while RSW data is probably higher than previously discussed. Although the generation rate of RSW is much lower than that of MSW, rural China faces greater difficulties in RSW management and service support in rural areas than that of MSW in urban areas.

Based on Table 2, it is observed that the compositions of RSW and MSW are extremely homogenous. Generally, waste composition in rural China is dominated by ash and organic waste, as analyzed previously. In contrast, the overwhelming majority of MSW composition is organic waste (more than 50%). Besides, the proportions of recyclable compositions in RSW are far less than that of MSW. Indeed, with the urbanization and rapid economic development of rural China, the proportion of recyclable waste will definitely increase in the future.

Applying the MSW management method would be unconscionable for rural China. Since the generation rates and compositions of RSW are diversified across regions, it would be necessary for local governments in different regions to adjust the RSW management approaches, including the methods of source-separated collection of RSW according to local conditions. Hence, considering the similarities of the RSW generation rate and the composition in rural areas of the same region, such as southern China, northern China, or eastern China, solutions can be focused on separately [10].

3 Current Status of RSW Management

3.1 RSW Collection, Separation, and Recycling

For rural China, one of the most popular means of RSW collection is carried out by the specific collection containers offered by local authorities. A centralized facility at roadside, usually called a refuse chute, which is made of cement or is just a natural pit, has been widely introduced, while in developed rural areas, outdoor trash cans have been widely implemented, which can reduce the risk of waste exposure, mosquito and fly growth, as well as odor occurrence. In addition, in many rural areas, such as small and remote villages, or in hilly or mountainous areas, RSW is not considered in the modern waste management system.

Systematic RSW separation and recycling are not implemented in rural areas, whereas only several pilot programs have been reported. As reported that MSW is collected in a mixed state in China [11], it likewise holds true for RSW that all sorts of RSW is mixed together and thrown into the refuse chute. Nevertheless, there is a voluntary source-separated collection of recyclables that exists for rural residents or scavengers.

Similar to MSW recycling [11, 14], informal sectors including some rural residents or scavengers are also involved in the collection, processing, and trading of the recyclable waste to buyers, who call door to door or sometimes deliver recyclables to the service sites themselves in order to exchange money. The buyers then store and, in turn, sell the recyclables to an upper level of recycling service sites in the county or somewhere else. Finally, recyclable waste is provided for the demands of industry as raw or processed material. Nevertheless, the amounts of recyclable waste informally picked out of the RSW stream are unknown.

3.2 RSW Treatment and Disposal

China initially established the fundamental mode of household separation, village collection, township transfer, and county treatment in some provincial pilot programs (not very far from the urban region) for RSW management, which has achieved noticeable progress (Fig. 2). In 2010, the first list of 28 counties (districts or cities) was released to the public by MOHURD due to the full coverage of RSW treatment at the county (district and city) level. The distribution of these 28 countries is shown in Fig. 3. These areas were mainly in relatively developed regions, including the Beijing, Jiangsu, Fujian, Anhui, and Guangdong provinces. However, the implementation of this mode in most remote rural areas was restricted by many factors, for example, the high transport cost and the lack of manpower and budget to supervise at the bottom of the local authorities and the local environmental protection bureau.

After being transported to the county or above the county level for downstream treatment and disposal, the applied technologies are mostly the same as that of MSW, including sanitary landfill, incineration, and composting. Table 3 lists the application status of MSW treatment technologies in China in 2012, showing that sanitary landfill is the dominant disposal method.

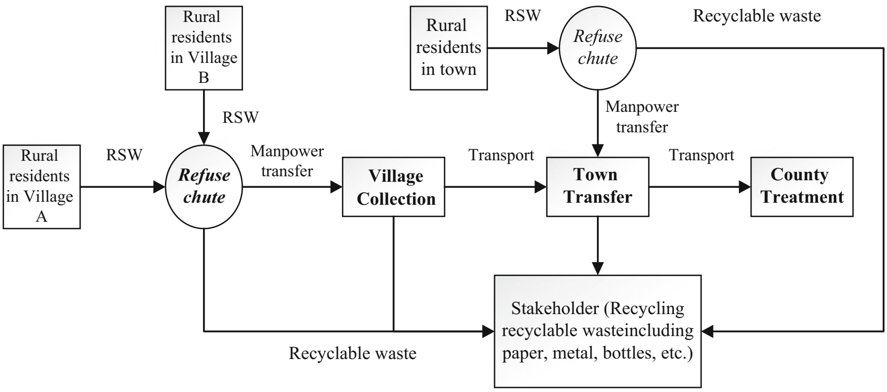

Fig. 2 Framework for the mode of household separation, village collection, township transfer, and county treatment for RSW management

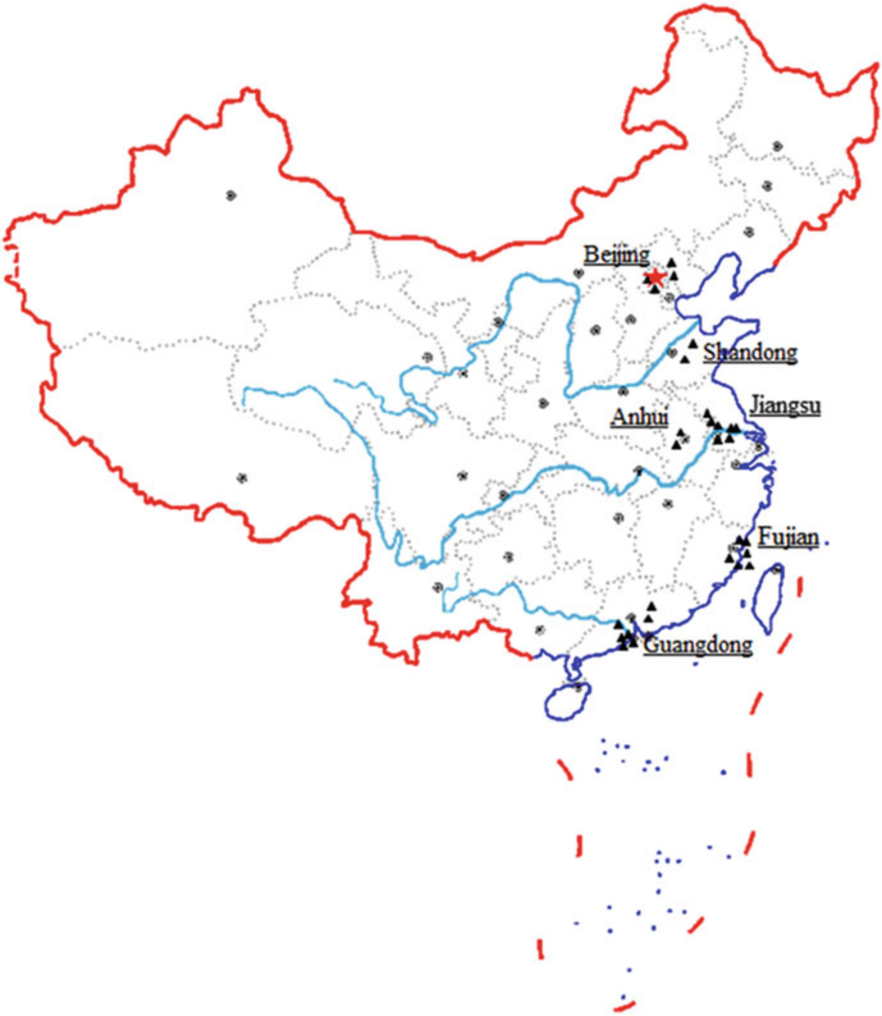

Fig. 3 Locations of 28 counties (districts or cities) for the full coverage of RSW treatment at the county (district and city) level

Table 3 Application situations of MSW treatment techniques in 2012

Technology	Landfill	Incineration	Other
Facility quantities	540	138	23
Proportion (%)	77	19.7	3.3
Harmless disposal capacity (tons/day)	310,927	122,649	12,692
Harmless disposal amount (10^4 tons)	10,512.5	3,584.1	393

In addition to the formal mode for RSW management, however, most RSW is discarded randomly, incinerated temporarily, or dumped on the river banks and the roadsides, often without any initial treatment but generally with agricultural and forestry waste, industrial solid waste, and even with household hazardous waste, which not only takes up land but also causes contamination and secondary pollution. For instance, as a disposal method, hazardous waste paints, cleaners, varnishes, batteries, and pesticides are often mixed with household waste [15]. Although its amount is small, it can cause considerable negative impacts on human health.

3.3 Case Study: The Town of Guoyuan in Changsha County, Hunan Province

Changsha County in Hunan Province is well known in China for the reputation of the Top One County of central China. It was chosen to be 1 of the 18 representative areas during reform and openness by the government. The first environmental protection cooperative was established in the town of Guoyuan in Changsha County in 2008, the highlight of which was that the cooperative purchased RSW from rural households and promoted the rural residents' participation for waste recycling and collection. It established collection spots in every village, and the prices for recyclable waste of plastics, batteries, and glasses were 0.04 USD kg^{-1}, 0.09 USD kg^{-1}, and 0.01 USD kg^{-1}, respectively. Moreover, the local government provided a subsidy of 0.43–0.72 USD to the rural households that participated. In 2012, the total financial investment in Changsha County reached 3.6 million USD, which improved the serious situation of RSW management.

From 2011 on, the cooperative upgraded the mode of household collection to household separation and required rural residents to dispose of food waste by composting themselves in order to conserve financial budgets. Otherwise, after being separated and collected, RSW would be separated again before the town transfer. Finally, an amount of less than 10% RSW was sent to the county for downstream disposal. In particular, it was estimated that the total waste disposal expense decreased from 4.4 million USD to 434.9 thousand USD [16].

3.4 Problems and Challenges in RSW Management

3.4.1 Decentralized Multiple Generation Sources

RSW management is confronted with a dilemma of a large amount of total generation nationwide that is decentralized across regions, which significantly increases the costs of waste collection, transportation, treatment, and disposal. Therefore, informal collection and recycling still play a significant role in rural areas. RSW treatment is going through a critical phase because suitable technology is unavailable, e.g., some have fatal drawbacks like geographical restrictions, high costs for operation, or a strong preference for one kind of waste, while some can achieve benefits only under a certain processing scale. Based on this, it is possible that RSW pollution is more serious than that of MSW.

3.4.2 Poor Infrastructure Construction

RSW management infrastructures include collection, transport, treatment, and disposal facilities like trash cans, vehicles, transfer stations, etc. Refuse chutes at roadsides for RSW collection are not enough at all. Poor infrastructure significantly contributed to the fact of irresponsible dumping of RSW. As a result, the phenomenon of *Garbage Besieging Villages* is often reported. And worst of all, it is still far from enough to make up for the inadequacies nationwide.

3.4.3 Imperfect Legislation System

The primary formulated legal system for RSW still has many shortcomings, because most of the legislation and administrative regulations were intended to treat the MSW, which essentially did not consider the RSW characteristics in China. Besides, specific national guidelines to enforce published laws are absent in Chinese laws; hence the unclear responsibility mechanism makes it more ineffective in RSW management. Moreover, there are many equivocal words in the related laws and regulations of RSW, such as *should*, *recommend*, *encourage*, and *can*, which mitigate against implementing these laws. Like so much in China, the legislative process of environmental protection is always led by the government, while the part of public participation is often overlooked.

4 Public Opinion Toward the Source-Separated Collection of RSW

China faces a different situation in RSW management than other developed countries. Meanwhile, the way of source-separated collection of solid waste in rural areas is different from urban areas in China. Generally, an individual is either active or reluctant to participate, mainly due to personal environmental beliefs. Therefore, rural residents' public opinion toward the source-separated collection of RSW was examined for a better implementation of the program in the future, based on a well-designed questionnaire and face-to-face interviews [5].

4.1 Empirical Design of the Questionnaire

The questionnaire was based on focus group discussions among the professors, doctoral candidates, and postgraduate students of Tongji University, who devote themselves to research on solid waste management, and specifically, most of them were born in rural China, so they are familiar with rural residents. After a series of group discussions, the questionnaire was drafted, then evaluated, and modified by two experts who devote themselves to rural issue studies and surveys. A pretest on 12 rural residents was conducted in order to uncover possible misinterpretations of the questions and to determine the bids in the final questionnaire.

The questionnaire consisted of four parts.

- The first part included questions related to the behaviors and perceptions of rural households toward RSW treatment and disposal and whether they were satisfied with local RSW management.
- The second part included a series of questions about the attitudes, awareness, and knowledge toward the source-separated collection of RSW. The respondents were interviewed about the importance of RSW separation, the sources of information about RSW separation, and their willingness to participate. Rural households who gave positive feedback were further requested to choose an acceptable waste separation category, while those who were not willing to participate, or willing to participate but could not participate in waste separation continuously, were requested to answer a follow-up question on the reasons for their choice.
- The third part included questions about respondents' willingness to pay (WTP) for RSW separation and management. In order to avoid the impatience of rural residents during the interview, this study used a payment card format rather than the dichotomous choice format. For respondents' better understanding, a specified scenario was given as follows: In order to create a better rural environment, the implementation of RSW source separation and environmental management will need a cost. Although the government may finance this program, it may not be enough. In case the village committee or community requests your family to pay for the program every month, are you willing to pay for it? Respondents, who answered yes, were then confronted with five bids (0.14, 0.29, 0.43, 0.58, and 0.72 USD) and requested to choose their maximum WTP for the program, while those who were not willing to pay were required to describe the reasons for the choice.
- The fourth part collected respondents' socioeconomic information, including gender, age, education, annual household income, local resident population, and dwelling place, which was used to determine the personal attributes.

An empirical model – a logistic model – was applied to examine the factors that affect the WTP of the rural households toward the RSW separation and management. The model is shown as follows:

$$\text{Log}\, P_i/(1 - P_i) = Z_i = \beta_0 + \beta_i X_i + e$$

where $P_i = 1$ if the respondent is willing to pay for the RSW separation and management; otherwise, $P_i = 0$; β_0 = constant term; β_i = the coefficient of independent variables; X_i = a vector of explanatory independent variables; and e = a random error term. The independent variables of this model are gender, age, education, annual household income, local resident population, and location and perception of RSW treatment, and the model can be expressed as below:

$$\begin{aligned}\text{WTP} = \beta_0 + \beta_1\text{Gender} + \beta_2\text{Age} + \beta_3\text{Education} + \beta_4\text{Income} + \beta_5\text{Population} \\ + \beta_6\text{Location} + \beta_7\text{Perception} + e\end{aligned}$$

Assuming that negative values do not exist for RSW separation and management, the mean WTP is calculated by using the formula of

$$\text{WTP} = \left(\sum (P_i \times N_i)\right)/N$$

where P_i = rural household's average acceptance of bid (USD/month); N_i = No. of rural households that accepted the average bid; and N = No. of rural households that gave a positive WTP.

4.2 Survey and Sampling Method

With special considerations on geographical distributions, socioeconomic characteristics, and budget constraints, the survey was carried out in 2 months (from January to February 2015) in three regions of mainland China, including the eastern region (Shandong, Jiangsu, Zhejiang, Fujian, and Guangdong Province), central region (Shanxi, Anhui, Henan, Hubei, and Hunan Province), and western region (Guizhou Province and Chongqing City). Locations of surveyed rural areas are presented in Fig. 4. In each province, at least one town consisting of several villages was chosen randomly to survey. To ensure that the results are representative of the entire region, the interviewees were randomly selected among the villages. Specifically, all respondents were from the village. Meanwhile, the interviewee was aware of the overall situation of his/her household.

Special attention was paid on two points. Firstly, face-to-face interviews were conducted in the research. Secondly, instead of an individual basis, rural households were chosen as the unit of sample and analysis. During the survey, the interviewer was guided by a village cadre (i.e., village party secretary, village head) who understood the dialect and was acquainted with local residents. Thirteen

Fig. 4 Locations of surveyed rural areas

postgraduate students and doctoral candidates who major in environmental engineering at Tongji University participated in the interviews. A total of 541 questionnaires were received, and 518 valid questionnaires (95.75%) were obtained after removing the questionnaire in which the respondents misunderstood the questions (including incomplete or inconsistent questionnaires). Sample distributions are as follows: 188 questionnaires were collected from 8 towns with 16 villages in the eastern region, 252 questionnaires from 7 towns with 14 villages in the central region, and 78 questionnaires from 2 towns with 4 villages in the western region.

To supplement the information obtained from the survey, some informal discussions were held with local cadres (i.e., village party secretary, village head), rural residents, informal sectors, and waste transfer workers in various villages to obtain a better knowledge of real situations and collect as many public perceptions as possible.

4.3 Socioeconomic Characteristics of Respondents

Socioeconomic characteristics of the respondents are presented in Table 4. The respondents were 56.8% male and 43.2% female. 66.5% of respondents were

Table 4 Socioeconomic characteristics of the respondents

Item	Response	No. of respondents	Percentage (%)
Gender	Male	294	56.8
	Female	224	43.2
Age group (year)	18–25	133	25.7
	26–35	114	22.0
	36–45	108	20.8
	46–60	123	23.7
	>60	40	7.7
Education	Primary school or lower	55	10.6
	Junior high school	211	40.7
	Senior high school or secondary technical school	116	22.4
	Junior college	56	10.8
	Undergraduate or above	80	15.4
Annual household income	0 USD up to 1,450 USD	54	10.4
	1,450 USD up to 2,899 USD	107	20.7
	2,899 USD up to 4,348 USD	116	22.4
	4,348 USD up to 5,798 USD	57	11.0
	>5,798 USD	184	35.5
Local resident population	1	7	1.4
	2	75	14.5
	3	147	28.4
	4	124	23.9
	5	109	21.0
	6	30	5.8
	7	14	2.7
	8	4	0.8
	9	5	1.0
	10	3	0.6

between 26 and 60 years old. Only 15.4% of respondents had any higher education. The average local resident population in one rural household was 3.91, probably revealing a consequence of the One Child Policy. Only 35.5% of the rural households had an annual income higher than 5,798 USD. That might be because some respondents were conservative and unwilling to answer with their real income.

4.4 Behaviors and Perceptions Toward RSW Treatment

Rural household behaviors toward RSW treatment and disposal were investigated, and 65.1% of rural households dumped RSW into the refuse chute or trash bin, but only a few villages in the eastern region had well-controlled collection, transportation, and treatment of RSW. 14.29% of rural households burned RSW out in the open without any pollution control system. 31.08% of rural households just dumped RSW on the moat banks and the roadsides, even without any initial treatment.

The potential of source separation behavior with RSW in rural households was also investigated and was shown in Table 5. The percentages of mixed dumping for food waste, recyclable waste, and hazardous waste were 67.8%, 21.9%, and 75.1%, respectively, which reveals that most RSW is dumped mixed. Owing to Chinese eating habits, one of the main fractions of RSW is food waste [10]. It was also found that good potential for the in situ utilization of food waste existed, as rural households used food waste for composting or biogas production (4.5%) and animal feed (15.5%). Meanwhile, 75.8% of rural households sorted out their recyclable waste for selling. Similar to MSW recycling in China, rural households are used to trading the recyclable waste to buyers who are called door-to-door traders (50.3%) or sometimes selling waste to the service sites by themselves (25.5%). This evidence proves that some rural households do have the behaviors of source-separated RSW collection, although most of them only separate their recyclable waste.

The respondents were requested to comment on the status of RSW treatment and disposal in their village. Only 23.8% of the respondents were satisfied with the RSW treatment in their villages. The result indicates that is mostly because local governments invest in the construction of refuse chutes or provide trash cans only. These collection and storage facilities strengthened the pollution control of RSW.

Table 5 Initiative behaviors toward different kinds of RSW in rural households

Items	No. of rural households	Percentage (%)
Food waste		
No food waste was produced and dumped	63	12.2
Used for composting or biogas, feedstuff, etc.	23	4.5
Partially used for livestock and poultry feed, the rest dumped	80	15.5
Mixed dumping	350	67.8
Recyclable waste		
Delivered to the recycling collection sites in the village	132	25.5
Waited for informal sectors' door-to-door service	260	50.3
Mixed dumping	113	21.9
Other	12	2.3
Hazardous waste		
Sent to specialized sites for hazardous waste	38	7.3
Discarded randomly, such as in fields, on river banks and roadsides, etc.	75	14.5
Mixed dumping	389	75.1
Other	16	3.1

Meanwhile, the percentages answering "average" and "unconcerned" were 30.0% and 7.7%, respectively. However, more respondents (38.5%) were unsatisfied with RSW management. The reasons could be summarized as follows: no specific worker was responsible for the collection and cleanup of RSW, the storage room (i.e., refuse chute, trash can) was close to their home, and the foul odor from the storage room created dissatisfaction. It indicates that RSW management is neglected or out of order in these areas. The interviewees also regarded RSW as one of the most serious environmental problems, which echoed the findings of previous research [4, 17, 18].

4.5 Awareness of the Environment and Source-Separated RSW Collection

In recent years, the central government has placed growing attention on the pollution in rural China. A series of laws and regulations related to RSW have been issued. Some pilot programs have been launched to find a feasible and suitable treatment process in different rural areas [10]. During the survey, it was found that in some rural areas, also public is aware of the source-separated collection of RSW. However, 10.4% of respondents were not conscious of the importance of the source-separated collection of RSW, while most respondents, accounting for 75.0%, considered that RSW separation could alleviate environmental pollution and negative health impacts. Meanwhile, 45.1% of respondents thought that they could separate recyclable waste for selling, and 44.1% knew that RSW separation could reduce the quantity of disposed RSW and save transportation expense. Although a relatively high awareness is not necessarily consistent with practical actions [19], it will be a basis for implementing the program of RSW separation at the source in rural China in the future. This result indicates that the difference in people's awareness on the importance of waste separation between rural residents and urban residents is not obvious in China, compared with previous studies [18].

The sources of information on source-separated RSW collection are summarized in Table 6. 72.7% of respondents obtained their knowledge from television and 31.6% from the newspaper. It was found that internet and community education are

Table 6 Sources of information about source-separated RSW collection

Response		Newspaper	Television	Radio	Community education	Others	Internet	Other
No.		162	372	67	96	78	120	18
Age groups (year)	18–25	64	112	19	23	30	57	9
	26–35	39	86	14	14	13	31	5
	36–45	29	74	16	22	16	15	0
	46–60	23	75	9	31	15	14	2
	>60	7	25	9	6	4	3	2

also popular, which is probably related to personal habits. For instance, younger respondents widely use the internet, while middle-aged respondents are more easily impressed by the policy and education in the village. However, it was found that the community education of source-separated RSW collection is very shallow and lacks implementation. These results suggest that a sufficient publicity program that includes public education and various media sources should be introduced by the local government to help raise more awareness toward the source-separated collection of RSW.

4.6 Attitudes Toward Source-Separated RSW Collection

As presented in Table 7, the attitudes toward source-separated RSW collection were generally positive. More than half of rural households (61.3%) declared that they were willing to participate in the program. Moreover, 47.9% of rural households agreed to separate RSW into the four categories "food waste, recyclables, dry waste, and hazardous waste." However, 25.0% of the rural households were willing to participate in source-separated RSW collection but probably couldn't commit to the source-separated collection of RSW continuously, and 13.7% clarified that they refused to participate. The detailed obstacles were also investigated and presented in Table 7.

A more detailed survey of barriers of rural households for RSW separation was carried out, and the results are present in Fig. 5. Rural households among the three regions considered the lack of separation awareness (64.9%) to be the major barrier to implement the program of RSW separation at the source. Complications,

Table 7 Comparison of different attitudes toward RSW separation participation

	No. of rural households	Percentage (%)
Positive participation	317	61.3
Rejection of participation	71	13.7
Inconstancy of participation	129	25.0
Positive participation		
Food waste, recyclables, dry waste, hazardous waste	152	47.9
Recyclables, hazardous waste, other waste	83	26.2
Food waste, dry waste, hazardous waste	45	14.2
Recyclables, nonrecyclables	37	11.7
Rejection of participation or inconstancy of participation		
Negative neighbor effect	33	16.5
Complication and inconvenience of separation	111	55.5
Mixed transport and disposal after separating at source	37	18.5
Other	19	9.5

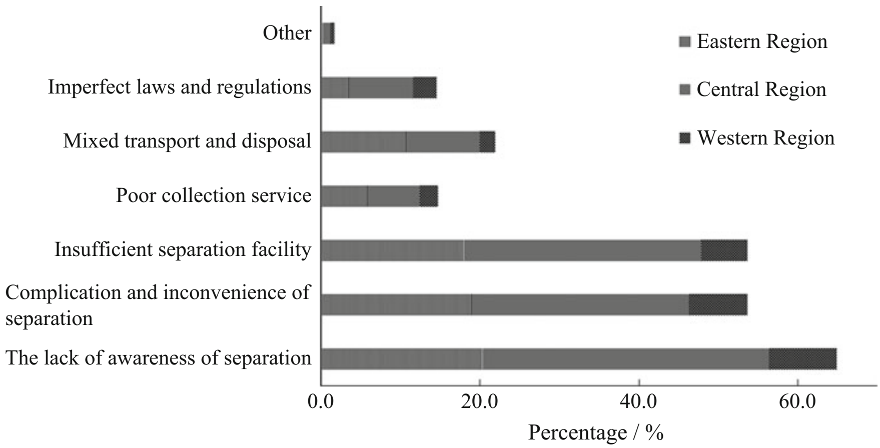

Fig. 5 Rural household barriers to RSW separation

inconvenience of separation, and insufficient separation facilities accounted for the same percentage of 53.7%, both of which were the second major barrier and might have a great influence on people's participation. Therefore, it is essential to provide sufficient separation facilities (i.e., garbage cans, storage room) for RSW separation and improve rural households' awareness, which is vital to public participation.

4.7 Estimation Results of WTP Toward RSW Separation and Management

The rural households who were willing to pay for RSW separation collection and management are regarded as having a positive WTP, and their opinions on the cost and payment method were also investigated. Otherwise, if they were unwilling to pay, they were asked a follow-up question concerning the reasons. The rural households who answered "have no extra money," "do not believe that RSW source separation and management would bring desired changes," or "refuse to pay, but otherwise would participate in RSW separation collection" are regarded as having a valid zero WTP. The rural households who answered "it is government's responsibility to improve RSW source separation and treatment" or "those households who throw away RSW should be responsible to pay," as well as "other," are treated as having rejected the contingent market. The WTP values of the rural households in these categories are summarized in Table 8. In total, 324 rural households (62.5%) reported a positive WTP, while 140 rural households (27.0%) reported a valid zero WTP, and only 54 rural households (10.4%) reported a rejection of the contingent market.

Table 8 Comparison of positive WTP, valid zero WTP, and rejection of contingent market

Comparison of positive WTP, valid zero WTP, and rejection of contingent market	No. of rural households	Percentage (%)
Positive WTP	324	62.5
Valid zero WTP	140	27.0
Have no extra money	38	7.3
Do not believe that RSW source separation and management would bring desired changes	64	12.4
Refuse to pay but otherwise would participate in RSW separation collection	38	7.3
Rejection of the contingent market	54	10.4
It is the government's responsibility to improve RSW source separation and treatment	33	6.4
Those households who throw away RSW should be responsible for paying	16	3.1
Other	5	1.0

Table 9 Results from the binary logistic regression (WTP >0, $n = 324$)

Variables	*B*	S.E.	Wals	df	Sig.	Exp (*B*)
Gender	0.192	0.194	0.987	1	0.320	1.212
Age	0.285	0.099	8.225	1	0.004***	1.330
Education	−0.066	0.108	0.366	1	0.545	0.937
Annual household income	−0.168	0.075	5.020	1	0.025***	0.845
Local resident population	0.097	0.066	2.168	1	0.141	1.102
Location	−0.722	0.159	20.641	1	0.000***	0.486
Perceptions of RSW treatment	0.050	0.106	0.225	1	0.635	1.052
Constant	−0.045	0.861	0.003	1	0.958	0.956
−2LL	636.403					
Cox and Snell R square	0.088					

***Significant at $p \leq 0.05$

Factors that affect the rural households' WTP toward the RSW separation and management were explored by using a logistic regression model (as described before). The respondents who were willing to pay for RSW separation and management and selected their WTP were given the value of "1," while those who were unwilling to pay were given the value of "0." Results from the binary logistic regression are presented in Table 9. It was found that respondents' age, annual household income, and location significantly influenced the WTP (at the 5% level). Besides, the correlation between WTP and annual household income as well as location was negative, while the correlation between WTP and age was positive. The results obtained in this research show that a considerable portion of respondents with higher incomes in the eastern region of China had a lower WTP than that of other regions. However, it was regarded that those with a higher household income have the ability to pay [18]. Such a discrepancy could be explained as the result of the situation that RSW management systems in higher GDP areas are running better, and the rural households there usually have already paid for waste management. Those with lower incomes usually face more serious RSW pollution, and hence they are more likely to pay for RSW separation and management in order to improve the environment. The elder respondents were more likely to pay, and this was because older people are often involved in RSW treatment and disposal and thus are more concerned about environmental quality. The results suggest that it is important to consider regional differences, including location and GDP, when implementing the program of RSW separation at the source. Meanwhile, targeted public education can be adopted to involve young people and those with higher incomes in the program.

The estimated mean WTP toward the RSW separation and management is 0.32 USD/month, meaning a rural household in the entire sample would support approximately 3.8 USD/year. This result is lower than that of previous studies about the estimation of WTP toward RSW management in rural China [17]. Based on this result, one can see that the economic development and levels of RSW management between rich rural areas and poor rural areas are unbalanced. The WTP for source-separated RSW collection is related to the GDP and waste management level. In some rich rural areas, the public is more satisfied with the current RSW management system and environmental quality than in those low-income rural areas. So currently, the urgent effort is to establish an RSW management system in poor rural areas as a priority, rather than the improvement of RSW management in rich rural areas. This assumes there are approximately 10,000 rural households in a representative town. The aggregate value of WTP in rural households would be $(10{,}000 \times 3.8) = 380{,}000$ USD, which shows considerable potential for local governments to provide services for RSW separation and management.

4.8 Policy Suggestions

To reduce the RSW pollution in rural China, the following measurements could be considered.

Firstly, policymakers should take the opportunity to transform rural households' willingness and awareness into action, because rural households urgently expect the government's effort on RSW management, and they have a strong intention to support source-separated RSW collection. Based on the current situation, it is feasible to implement a pilot program of RSW separation at the source in rural China.

Secondly, policymakers should consider the cost and financial support, especially for the facility and collection service of the program of RSW separation at the source. This is also the concern of rural households. It is therefore of utmost importance to add state allocations to rural households to implement the program. Local governments should also examine the number of WTP budgets for RSW separation and management, although an appropriate payment, according to the survey, would be acceptable to most rural households. Two payment methods, including "pay by amount of RSW" and "equal charge standard for every household," are more popular, accounting for 37.3% and 34.6% of the rural households (among those willing to pay), respectively.

Continuous efforts to raise public concerns about environmental awareness and behaviors through education and publicity, including RSW separation, reduce, reuse, and recycle, should be made as soon as possible. The discrepancies of villages across rural areas are also worth considering. Similar investigations are needed for the future implementation of source-separated RSW collection accordingly, since public perceptions and determinants may be different across regions due to the disparity of socioeconomic backgrounds.

5 Recommendations and Expectations for the Future

In recent years, China has recognized the critical situations of RSW and has devoted considerable efforts to promoting RSW management. As a result of the improvement of related laws and regulations, financial support, and investment infrastructure, RSW management is relatively developed. However, the RSW management system still represents smaller parts of rural areas. RSW characteristics differ considerably across regions of China, since the survey results of RSW generation rates range from 0.25 to 2.1 kg (capita d)$^{-1}$. The fundamentally formal separation of waste in households, village collection, township transfer, and county treatment for RSW management has been partially established in rural areas.

Since most of the RSW is still discarded randomly without any initial treatment, source separation and waste recycling are regarded as effective methods to minimize waste from the source. Based on the investigation of public perceptions on source-separated RSW collection in rural China, it can be concluded that most respondents are aware of the importance of RSW separation and more than half of rural households are willing to participate in the separation program. The WTP for RSW separation and management is significantly influenced by respondents' age, annual household income, and location. Here, the mean WTP is estimated to be 3.8 USD/year. To improve RSW management in rural China, especially in poor rural areas, the establishment of a waste separation system is an urgent duty. The separation method (waste category, sorted waste collection schedule, etc.) needs further research. After collected separately from residents, the inorganic waste and nonrecyclable waste can be separated in the village again. Finally, different wastes can be separately treated and disposed of according to local conditions. On-site treatment of RSW in villages or towns could help to reduce the cost of waste transportation.

References

1. Huang KX, Wang JX, Bai JF, Qiu HG (2013) Domestic solid waste discharge and its determinants in rural China. China Agric Econ Rev 5(4):512–525
2. Aphale O, Thyberg KL, Tonjes DJ (2015) Differences in waste generation, waste composition, and source separation across three waste districts in a New York suburb. Resour Conserv Recycl 99:19–28
3. Babaei AA, Alavi N, Goudarzi G, Teymouri P, Ahmadi K, Rafiee M (2015) Household recycling knowledge, attitudes and practices towards solid waste management. Resour Conserv Recycl 102:94–100
4. Tai J, Zhang W, Che Y, Feng D (2011) Municipal solid waste source-separated collection in China: a comparative analysis. Waste Manag 31(8):1673–1682
5. Zeng C, Niu D, Li H, Zhou T, Zhao Y (2016) Public perceptions and economic values of source-separated collection of rural solid waste: a pilot study in China. Resour Conserv Recycl 107:166–173
6. Li Y, Xu SH (2007) Current situation and countermeasure of rural domestic solid waste in China. Constr Sci Technol 7:62–63. (in Chinese)
7. Ye CH, Qin P (2008) Provision of residential solid waste management service in rural China. Chin World Econ 16(5):118–128
8. Wang JQ, Wang YB, Li XC, Xue JR, Zhang YH (2004) Discharge and disposal status on domestic garbage and sewage in countrysides. Chin J Public Health Eng 3(4):202–205. (in Chinese)
9. Wei X, Liu XL, Su Y (2007) Characteristics of pollution in rural habitats and analysis on caution: a survey based on the status quo of China's rural drinking water and environmental sanitation. China Dev 7(4):92–98. (in Chinese)
10. Zeng C, Niu D, Zhao Y (2015) A comprehensive overview of rural solid waste management in China. Front Environ Sci Eng 9(6):949–961
11. Zhang DQ, Tan SK, Gersberg RM (2010) Municipal solid waste management in China: status, problems and challenges. J Environ Manag 91(8):1623–1633
12. Surendra KC, Takara D, Hashimoto AG, Khanal SK (2014) Biogas as a sustainable energy source for developing countries: opportunities and challenges. Renew Sust Energ Rev 31:846–859
13. Shi BF (2011) Technical guide for municipal solid waste sanitary landfills. Research for National Standard and Engineering Application, Huangzhong University of Science and Technology, Wuhan (in Chinese)
14. Linzner R, Salhofer S (2014) Municipal solid waste recycling and the significance of informal sector in urban China. Waste Manag Res 32(9):896–907
15. Duan HB, Huang QF, Wang Q, Zhou BY, Li JH (2008) Hazardous waste generation and management in China: a review. J Hazard Mater 158(2–3):221–227
16. Zhang YM, Zhang CS, Sun XM, Du X (2014) Rural domestic solid waste treatment and recycling management. China Architecture & Building Press, Beijing. (in Chinese)
17. Wang H, He J, Kim Y, Kamata T (2014) Municipal solid waste management in rural areas and small counties: an economic analysis using contingent valuation to estimate willingness to pay for Yunnan, China. Waste Manag Res 32(8):695–706
18. Zhang W, Che Y, Yang K, Ren X, Tai J (2012) Public opinion about the source separation of municipal solid waste in Shanghai, China. Waste Manag Res 30(12):1261–1271
19. De Feo G, De Gisi S (2010) Public opinion and awareness towards MSW and separate collection programmes: a sociological procedure for selecting areas and citizens with a low level of knowledge. Waste Manag 30(6):958–976

Recycling of Biowaste: Experience with Collection, Digestion, and Quality in Germany

Klaus Fricke, Christof Heußner, Axel Hüttner, and Thomas Turk

Abstract Only cascading use can ensure higher sustainability in the recycling of biodegradable waste materials (biowaste) compared to pure thermal and/or energetic utilization types. Cascading use means, in a first stage, that energy is skimmed off by a fermentation process. In a second stage, products used as organic fertilizers and soil improvers are generated. This is usually done by composting. The separate collection of biowaste is a prerequisite for the production of high-quality organic fertilizers and soil improvers.

The anaerobic treatment of biowaste and green waste in Germany has not gained the importance it deserves by far, owing to its ecological advantages. This is also evidenced by the high expansion and development potential afforded by the anaerobic treatment. There is a need for action in two areas: (1) increase the amount of biowaste collected by establishing a tightly meshed nationwide expansion of the organic waste bin system and increase the collection rates and (2) channel a large proportion of the biowaste currently only undergoing composting into fermentation as well. The potential for increasing fermentation in Germany is estimated at 5.4 million tons.

Keywords Anaerobic digestion, Biowaste, Composting, Recycling, Source separation

Contents

K. Fricke (✉), C. Heußner, A. Hüttner, and T. Turk
Technical University of Braunschweig, Braunschweig, Germany
e-mail: klaus.fricke@tu-braunschweig.de

R. Maletz et al. (eds.), *Source Separation and Recycling*,
Hdb Env Chem (2018) 63: 175–198, DOI 10.1007/698_2017_34,

© Springer International Publishing AG 2017, Published online: 29 July 2017

1 Introduction

Only cascading use can ensure higher sustainability in the recycling of biodegradable waste materials (biowaste) compared to pure thermal and/or energetic utilization types. Cascading use means, in a first stage, that energy is skimmed off by a fermentation process. In a second stage, products used as organic fertilizers and soil improvers are generated. This is usually done by composting. The separate collection of biowaste is a prerequisite for the production of high-quality organic fertilizers and soil improvers.

The controlled anaerobic digestion of organic residues has long been a common practice in wastewater treatment (sludge) and agriculture (manures, slurries). Anaerobic technologies for the treatment of solid residues like biowaste and green waste were first applied in the beginning of the 1990s. During the implementation phase of the “selective collection and utilization of biowaste” system from 1988 to 1995, biodigestion technology had not yet reached the necessary development stage. It was not until the last 10 years that biodigestion had gained importance. Initially, the reluctance to apply the technology was due to technological and economic reasons. Technical shortcomings were attributed to functional failures across the whole process (mechanical and biological), as well as to remarkably high wear and tear.

The high investment and operating costs of anaerobic processes compared to aerobic processes initially impeded the establishment of the anaerobic technology despite its numerous ecological advantages. In the meantime, anaerobic technology has been continuously developed and optimized, while technical problems have been reduced to an acceptable level. On the economic side, the Renewable Energies Act [1] provided a favorable framework for the installation of anaerobic technologies. Anaerobic processes still require higher investment costs but have become more cost-effective than in the mid-1990s. Operating costs for anaerobic and aerobic technologies are now on the same level. This is because energy revenues can be obtained with anaerobic technologies, thanks to the Renewable Energies Act. Under certain circumstances, the anaerobic processes may even provide economic advantages.

The 65% recycling quota required by the German Waste Management and Product Recycling Act [2] and the requirement for the separate collection of biowaste in force since January 1, 2015, play key roles in the increased development of both biowaste processing and anaerobic technologies.

2 Material Flow Management of Biowaste and Green Waste

2.1 Status Quo and Potential Assessment of Biowaste and Green Waste Processing

The separate collection of biowaste and green waste in Germany has reached a high level of implementation. However, the proportion of energy produced from these waste types is still comparatively small. Biowaste and green waste are mostly processed by composting. According to the German Federal Statistical Office, 9.8 million tons of biowaste and green waste were collected in 2014 (Fig. 1). Processing takes place at 990 composting facilities and approximately 100 anaerobic treatment plants. Around 2 million tons of biowaste and green waste are treated in anaerobic facilities. The quantities of previously collected, anaerobically processable biowaste and green waste still presently channeled to composting account for 3.9 million additional tons per annum (Table 1). With the nationwide implementation of separate biowaste collection mandated by the German Waste Management and Product Recycling Act on January 1, 2015 [2], this amount can be increased by another 1.5 million tons to about 5.4 million tons a year.

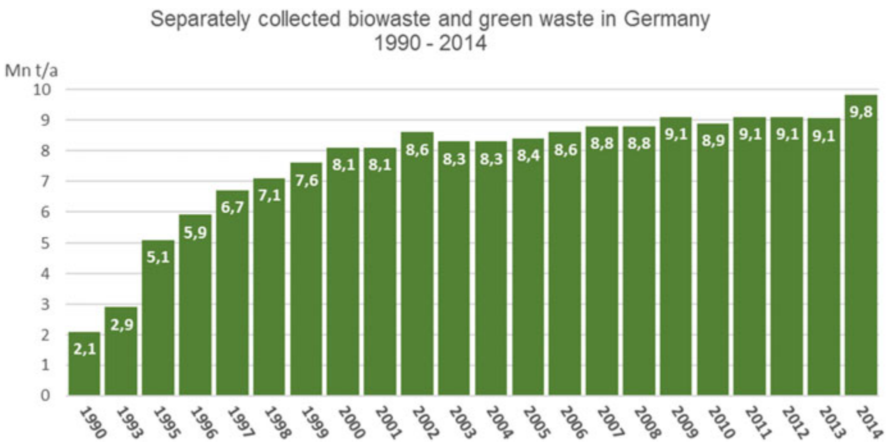

Fig. 1 Separately collected biowaste and green waste in Germany 1990–2014

Table 1 Projected total quantities of biowaste and green waste also available for anaerobic digestion in Germany

	Biowaste (t/a)	Green waste (t/a)	Total (t/a)
Amount of biowaste and green waste in 2014 (separately collected)	4,602,900	5,228,600	9,831,500
Fermentable potential (85% of biowaste, 30% of green waste)	3,912,465	1,568,580	5,881,045
Existing fermentation capacity for biowaste and green waste			Approximately 2,000,000
Additional expansion potential for anaerobic digestion of already separately collected biowaste and green waste			3,881,045
Additional expansion potential for anaerobic digestion given nationwide implementation of the organic waste bin			1,500,000
Aggregate additional potential for anaerobic digestion of biowaste and green waste			**5,381,045**

2.2 *Feedstock Quality and Quantity for Anaerobic Digestion*

Biowaste and green waste are subject to seasonal fluctuations in quantity and quality that create sizing problems for composting plants. In Germany, supply peaks are mostly observed in the summer and autumn, encumbering attempts to maintain constant utilization capacity. Besides suboptimal fermenter utilization, the low performance of biogas production can impair CHP unit utilization and, consequently, reduce electric efficiency. In the same way, the biological process is affected by fluctuations in feedstock quantity and quality, which in turn results in a decrease in gas production and reduced process stability. Green waste also undergoes impressive annual variations in amount and material composition. The problems relating to fermenter utilization and gas production described above are aggravated when suitable green waste is channeled into the anaerobic treatment facility. Late spring and summer are the seasons for digestible green waste, like grass cuttings, with comparatively high biogas potential. In the autumn, large quantities of dead leaves are available, albeit with low biogas potential. In winter, almost no green waste is available.

For the anaerobic treatment of biowaste and green waste to be efficient, a balanced supply throughout the year has to be targeted, at least in Germany and countries with similar climatic conditions. In other countries with seasonally balanced climates, these problems are not extant or only exist to a limited extent.

Organic kitchen waste has a significantly higher gas potential than garden waste. Leaves have particularly low gas potential (Table 2). However, collection rates for kitchen waste are considerably lower than for garden waste, as practiced in Germany. Therefore, measures need to be taken to improve the collection of kitchen waste, such as public relations work and controls to ensure proper disposal and collection. In

Table 2 Specific biogas production and quality of different feedstocks as a function of digester input

Raw material	Quantity (m^3/t fermenter input)	CH_4 (vol.-%)
Biowaste (mixture of kitchen and garden waste)	75–136	53–63
Biowaste (kitchen-generated)	123–178	53–68
Green waste (without wooden components)	40–90	50–61
Org. fraction of mixed waste (MSW)	100–174	57–62

urban areas with no or only minimal private garden areas, the high gas volumes for kitchen waste must be used for the plant sizing, as shown in Table 2.

2.3 Compost Quality Generated from Separate Collection and Mixed Waste (MBT)

Fundamentally, the question must be discussed as to whether it is imperative to collect kitchen and garden waste separately or whether it is also possible to sustainably utilize the kitchen and garden fractions from mixed waste.

A study on compost quality conducted by the European Commission's Joint Research Centre in ISPRA supplies valuable information relating to the discussion of this topic. ISPRA ran a spot-check and analysis within 15 European countries by taking 113 samples and analyses made from sludge compost, biowaste compost, green waste compost, and compost from mixed waste and/or mechanical biological treatment [3]. This study aimed to provide robust data for the end-of-waste (EoW) discussion. Likewise, the findings ought to allow conclusions about whether it is imperative that kitchen and garden waste be collected separately or whether it is also possible to sustainably utilize the kitchen and garden fractions from mixed waste.

Over the past few years, the reprocessing and conversion technology used in compost generation have improved markedly. This has allowed the concentrations of physical impurities and heavy metals in the compost generated from mixed waste to be reduced substantially. Nevertheless, compost from separate collections continues to have a significantly better quality than compost from mixed waste; this particularly applies to the two main parameters of physical impurities (glass, metal, plastic particles <2 mm) and heavy metals.

Figure 2 plots the physical impurities in compost samples collected by JRC and sent by plants. The red bar represents the proposed maximum value for EoW product criteria (Co, compost; BW, source-separated biowaste and green waste; GW, source-separated green waste; SS, sewage sludge; MBT, mechanical biological treatment). Compared to compost generated from mixed waste by MBT, separately collected biowaste composts contain markedly lower concentrations of physical impurities.

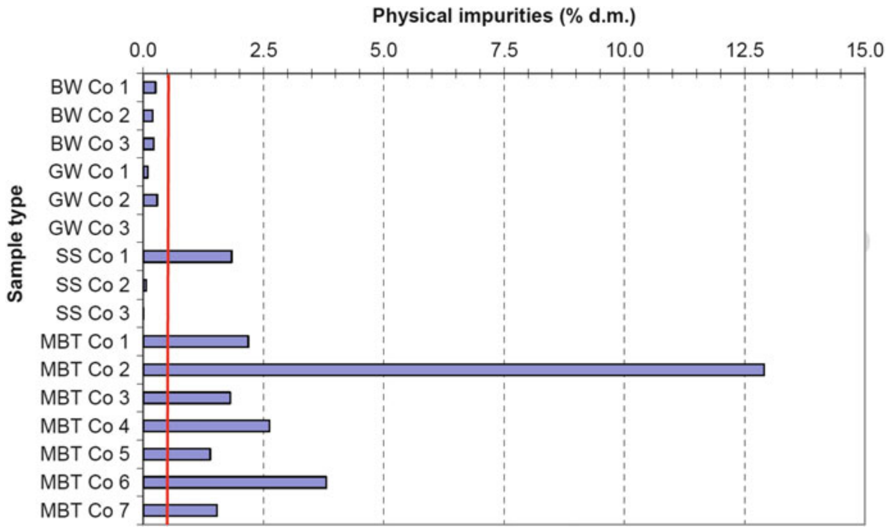

Fig. 2 Physical impurities (glass, metal, and plastic particles >2 mm) in compost samples collected by JRC and sent by plants

Table 3 presents the heavy metal loads of composts generated from mixed waste as compared with those from separate collections. The comparison shows that compost from source-separated collection exhibits the lowest overall heavy metal concentrations. When compared with the compost quality from the 1970s and 1980s, as was produced from mixed waste, for example, in Germany, there has been a marked decline in heavy metal concentrations.

The comparative analysis of the aforementioned studies by JRC-IPTS [3] yielded similar findings:

- "**Hg**: All samples met the proposed limit of 1 mg/kg dry matter.
- **Cr**: Nearly all samples met the proposed limit of 100 mg/kg dry matter, except one sewage sludge compost sample, one MBT compost sample, and one compost-like output from an MBT installation destined for landfilling.
- **Pb**: Nearly all samples met the proposed limit of 120 mg/kg dry matter, except four MBT compost samples.
- **Cd**: Most samples met the proposed 1.5 mg/kg dry matter limit value, except one green waste compost sample, one sewage sludge compost sample, four MBT compost samples, one digestate sample, and one other sample.
- **Ni**: Most samples met the proposed 50 mg/kg dry matter limit value, except four separately collected biowaste compost samples, one green waste compost sample, one sewage sludge sample, and one MBT compost sample.
- **Cu**: Compost from source-separated biowaste or green waste generally met the proposed limit value of 100 mg/kg dry matter, except for two samples (one in each category). Sewage sludge compost, MBT compost, and digestate hardly meet the

Table 3 Concentrations of heavy metals for compost from source-separated organic waste and from MBT of mixed waste (in mg/kg dry matter)

	Spain mixed waste compost MBT[a]	France mixed waste compost MBT[b]	France biowaste compost[b]	Austria biowaste compost[c]	Germany biowaste compost[d]	Germany mixed waste compost[e]
Data	2013	2007	2009	2010	2013	1980
CD	1.4	1.4	0.3–0.4	0.57	0.42	5.5
Cu	158	152	58–65	62	39	274
Hg	0.3	0.6	0.1–0.3	0.2	0.24	2.4
Ni	29	31	9–18	23	13.4	45
Pb	97	138	32–32	31	31.2	513
Zn	351	476	128–192	204	169	1,570

[a]Stabilized MBT – material: SCT, personal communication Carrera, 2013
[b]Stabilized MBT – material: Veolia/Copin – personal communication. Biowaste compost: two individual composting plants, personal communication to Bart. Documents from the French Quality Assurance Project ASOA, 2007
[c]Database of the Austrian Compost and Biogas Association; Data from 2010 to 2012
[d]Database of the German Federal Compost Association (BGK), personal communication, 2013
[e]Fricke et al. [4]

proposed limit values, with measured median values situated around the proposed limit value.

- **Zn**: Compost from source-separated biowaste or green waste generally met the proposed limit value of 400 mg/kg dry matter, except for one green waste compost sample. More than 20% of the sewage sludge compost, MBT compost, and digestate samples did not meet the proposed limit values."

Table 4 shows the trend in heavy metal concentrations in German biowaste composts. In recent years, a significant reduction in the burden has taken place. The causes are complex. A major source of the burden of composted raw materials includes wet deposits from air emissions that contaminate the composted raw materials directly and/or indirectly through the soil (primary source). An improvement in the concentrations of relevant heavy metals has been observed since the 1990s. This particularly applies to lead, mercury, and cadmium. The reduction in heavy metal deposits has most likely contributed to the decline in heavy metal concentrations in biowaste composts. Since there was no change in the grade of physical impurities during those years in Germany, this reduction can be excluded as a reason for the improvement, as can better pretreatment technology for eliminating physical impurities and contaminants, respectively. Hence, it is suggested that the heavy metal burden in kitchen and garden waste is declining.

Table 4 Heavy metals trends in biowaste composts in Germany (mg/kg dry matter)

	Biowaste compost 1991	Biowaste compost 1999	Biowaste compost 2012	Biowaste compost 2016	
	Median $n = 153$	Median $n = 2.510$[a]	Median $n = 2.691$[a]	Median $n = 3{,}345$[a]	Changing to 1991 (%)
Pb	63.2	52.7	31.2	31.3	−51
Cd	0.79	0.51	0.42	0.42	−47
Cr	33.0	25.6	22.0	20.5	−38
Cu	39.3	49.6	39.0	39.5	−0
Ni	18.6	15.9	13.4	13.1	−28
Hg	0.25	0.16	0.10	0.11	−70
Zn	182.9	195.0	169.0	160.1	−12

[a]Data from the German Federal Compost Association

3 Anaerobic Treatment Technology and Processes

3.1 Classification of Anaerobic Digestion Technologies/ Processes

The technologies and processes used for the anaerobic treatment of solid waste are different from the ones used for the anaerobic treatment of residues from wastewater treatment plants, residues from agricultural and industrial production, and renewable feedstocks. The differences become apparent in the anaerobic processes and in pre- and post-processing. The classification is based on the biodigestion process and the feeding process used for the substrate and not on the conditioning technology for the feedstock. Percolation under aerobic conditions is classified as wet conditioning; digestion itself is conducted in a wet anaerobic process. Processes that use presses are classified as dry conditioning, and wet or dry processes are applied depending on the desired quality of the output. The technologies and processes used for anaerobic treatment can be organized according to the different types depicted in Fig. 3. This system is the basis for describing the status quo on anaerobic treatment of biowaste and green waste in Germany.

3.1.1 Mesophilic and Thermophilic Processes

Degradation during anaerobic processes takes place due to the action of different organisms whose nature and performance are dictated by the process temperature. Optimum performance of the microorganisms occurs within two narrow temperature ranges. For practical applications, the relevant temperatures are in the mesophilic (approximately 34°C–42°C) and thermophilic (approximately 50°C–60°C) ranges. All processes can be operated with mesophilic temperatures, as well as with thermophilic temperatures.

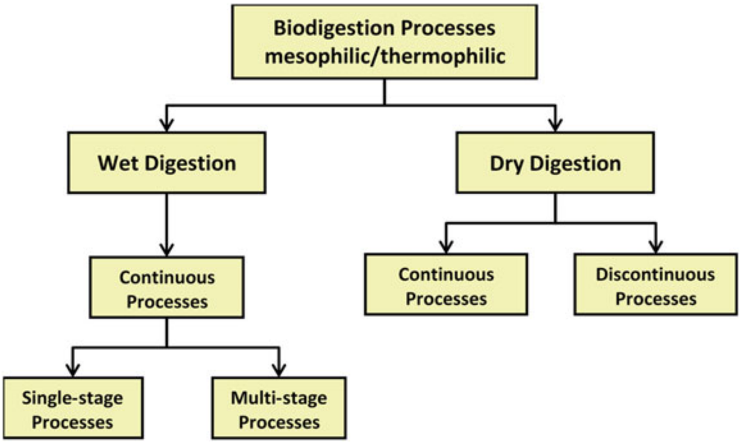

Fig. 3 Types of anaerobic treatment technologies and processes

3.1.2 Dry and Wet Processes

Anaerobic digestion processes can be divided into dry or wet, according to the dry matter content in the substrate fed into the fermenter. Dry process technologies can be further differentiated into continuous and discontinuous operations. Dry processes are operated with dry matter contents above approximately 30%. There is no limitation on dry matter content, which is determined by the input material. Biowaste and green waste usually have dry matter contents of 35%–50%. Wet processes are characterized by dry matter contents below 12%–15%, and the lowest values, for instance, in fixed-bed reactors, are below 1% dry matter.

3.1.3 Continuous and Discontinuous Dry Processes

Continuous processes are characterized by the addition of feed and the removal of corresponding amounts of digested substrate at regular intervals. A more or less continuous biogas production of constant quality is the result. In discontinuous processes – also known as batch processes – the fermenters (tunnels) are filled with raw substrate or sometimes mixed with predigested material and then closed. Over a period of 3–4 weeks, the material is irrigated with process water or percolate. This triggers the anaerobic degradation process and causes biogas to form in the tunnels and percolate reservoirs. Irrespective of an additional wet digestion stage of the percolate, the discontinuous processes are classified as dry processes – whereas some ambiguity cannot be avoided.

3.1.4 One-Stage and Two-Stage Processes

With the participation of various microorganisms, anaerobic degradation occurs in four successive steps: hydrolysis, acidification, acetic acid formation, and methanation. In single stages, all degradation steps take place in one vessel. Therefore, the environmental conditions cannot be adapted specifically to the individual requirements of the different microorganisms involved in the degradation. In two-stage processes, the hydrolytic step and the ongoing formation of low-molecular-weight acids take place separately from the methanation step. The separation of the steps allows better adaptation of the environmental conditions to the individual requirements of the microorganisms, however, and results in higher expenditures on technology, construction, and operations.

Conventional two-stage processes are restricted to wet processes. Process combinations consisting of an upstream aerobic process stage and a subsequent anaerobic process stage are known as quasi-two-stage processes. The most acidifying bacteria are facultative anaerobic and can metabolize in both the presence and absence of oxygen. The upstream aerobic stage is designed to bring about more effective hydrolysis and acidification. Heating to the desired mesophilic or thermophilic temperature levels can be achieved by the upstream aerobic process stage. Consequently, these processes are classified as one-stage processes in the system.

3.2 Status Quo of Anaerobic Digestion Technologies and Processes

By the end of 2014, 100 facilities with a processing capacity of about 2 million tons of biowaste and green waste had gone into operation. A total of 20 facilities operated with the wet process and 80 with the dry process. Of the facilities operating with the dry process, about 50% are continuously operated and 50% run the discontinuous process. The dominating position of the dry processes is also reflected by the single- and two-stage processes, because the conventional two-stage processes are restricted to wet processes. Only nine of 100 facilities run a two-stage process. Fifty-seven percent of the facilities operate within the mesophilic temperature range and 43% at thermophilic temperatures. The majority of the dry continuous processes are operated at thermophilic temperatures, whereas dry discontinuous processes are mainly operated at mesophilic temperatures.

In terms of the historical development of the construction of anaerobic treatment facilities for biowaste and green waste, the actual beginning of the anaerobic treatment of biowaste and green waste dates back to the mid-1990s. Before that time, only experimental and demonstration facilities had been in operation (Fig. 4). The most intensive construction of new facilities occurred after 2003.

Impressive advancements in process engineering and operation modes have been observed in the past few years. In the 1990s, the construction of wet processes was

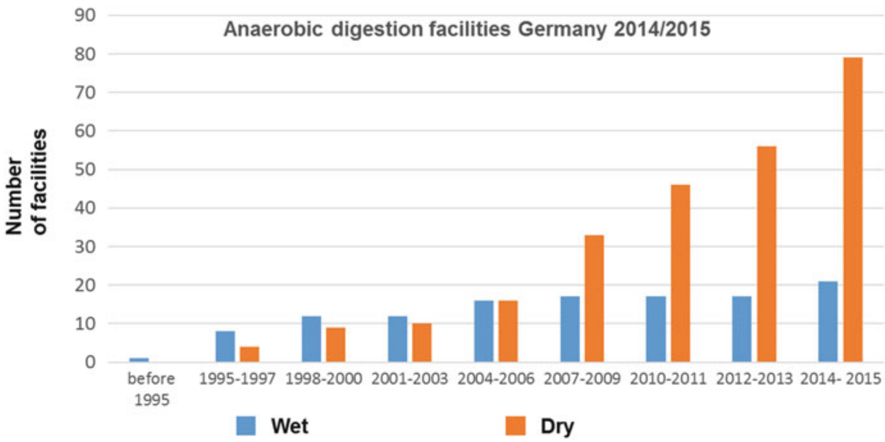

Fig. 4 Years after starting the operation of anaerobic treatment facilities for biowaste and green waste

predominant; half were single-stage and the other half, two-stage processes. In the 2000s, mostly dry processes were installed. The boom of dry discontinuous processes commenced in 2006, with 50% of the dry processes operating with the dry discontinuous process. In the beginning, this development was supported by the German Renewable Energies Act (EEG) based on subsidized dry processes [1].

In relation to single-stage or two-stage process engineering and technologies, the development was clearly in favor of single-stage processes. In the past several years, not one two-stage facility for the anaerobic treatment of biowaste and green waste has been put into operation, and no two-stage process which is among the facilities is under construction. Some well-known manufacturers only offer two-stage processes explicitly upon request.

A tendency toward thermophilic processes can be observed. For instance, at several locations with dry discontinuous processes, the transition to the thermophilic temperature range is envisioned. According to specialized manufacturers, the majority of facilities under construction plan to implement thermophilic processes. This is expected to achieve substrate hygienization as well as a higher biogas production.

The processing capacities of the anaerobic treatment facilities for biowaste and green waste currently in operation are all below 50,000 tons per annum. The majority of facilities installed capacities on the order of 10,000–30,000 tons per annum. Compared to waste incineration plants and composting plants, these capacities are low. The facilities currently under construction have higher capacities, mainly in the range of 30,000–70,000 tons per annum.

4 Energy Production

4.1 Basis for Calculation

The energy efficiency assessment is based principally on the energy production from the biogas produced and the energy consumption of the anaerobic digestion process. Consequently, this has to be considered in the overall context together with other factors, such as availability of the facility, lifetime of the equipment, and the energy requirements for construction and machines (cumulative energy requirement, CER).

The means for biogas quantities and methane content produced by the different technologies and processes are listed in Table 5. Dry continuous processes yield slightly higher quantities than wet processes. The high value observed for thermophilic wet processes is a singular observation and therefore hardly influences the mean. Dry discontinuous processes have lower biogas yields. The yield data in Table 5 refer to digester input, although relating biogas yield to the input of the facility is more meaningful because this value describes the real amount of energy produced per mg of biowaste. In wet and dry continuous processes, an average of about 20% (12%–30%) of the biowaste is separated during the preparation stage – prior to the anaerobic stage – and directly fed to the composting stage. Due to the separation of heavy components and grit, wet processes tend to show higher values. In dry discontinuous processes, the corresponding mean only approximates to 7% (0%–10%). Conversion factors have to be considered in order to convert the values (fermenter input) according to the input to the facility.

The quantities input into the facility decrease the specific biogas and methane quantities produced. In discontinuous processes, the specific biogas yield is only slightly reduced due to the lesser volume of waste separated prior to the anaerobic stage. However, the methane yield is more relevant for the energy assessment. Wet processes show higher concentrations of methane in the biogas, i.e., of about 63% v/v, compared to dry processes that reach mean values between 56 and 59% v/v. Since wet processes produce higher methane yields than dry continuous processes, the specific methane yields of both of these processes are almost at the same level. The mean specific methane yields of dry discontinuous processes are approximately 20% below the respective values of the continuous processes.

Thermophilic processes – considering the usually employed retention times – obtain impressively higher biogas and, therefore, higher methane yields across all technologies and processes (Table 5 and Sect. 5.1.3).

The following calculations are based on the data from Table 5. Combined heat and power (CHP) units are installed on more than 90% of the facilities in Germany. Electric and thermal efficiencies of 38% and 46%, respectively, were used for the calculation (see also Sect. 5.2).

For the assessment of the inherent energy consumption of anaerobic treatment facilities, not only the electricity consumption but also the fuel consumption of mobile equipment such as wheel loaders, mobile screens, and shredders have to be taken into

Table 5 Specific biogas and methane yields of different anaerobic technologies and processes for treatment of biowaste and green waste relative to the input to digesters and facilities [5]

Process		Biogas volume (m^3/t input fermenter)	Biogas volume (m^3/t input facility)	Methane content (%)	Methane volume (m^3/t input facility)
Wet	Total	111	89	63	56
	One-stage	106	85	62	53
	Mesophilic	100	80	62	50
	Thermophilic	130	104	63	66
	Two-stage	115	92	63	58
	Mesophilic	115	92	63	58
	Thermophilic	n.a.	n.a.	n.a.	n.a.
Dry	Continuous	122	98	58	57
	Mesophilic	109	87	59	51
	Thermophilic	123	99	58	57
	Discontinuous	87	81	56	46
	Mesophilic	87	81	56	45
	Thermophilic	91	85	56	48

account. Very little information is available concerning diesel fuel consumption; however, the obtained data correspond to our own findings. The diesel fuel consumption per mg of input into the facility, for intensive wet and dry processes and for dry discontinuous processes, was estimated at 1 and 1.5 L, respectively. The higher diesel consumption of dry discontinuous processes is due to loading and unloading the fermenters with a wheel loader. The energy content of the consumed diesel fuel is converted to kWh and added to the electricity consumption.

Based on the collected data, the wet processes have a higher overall energy consumption (combined electricity and diesel fuel consumption), at 65 kWh/t, compared to the dry continuous processes, at 48 kWh/t. The dry discontinuous processes have the lowest overall energy consumption, at 36 kWh/t. The low energy demand of the dry discontinuous processes, compared to the intensive wet and dry continuous processes, is mainly based on the need to prepare the feedstock, such as conditioning prior to feeding, and the nonextant demand for mixing during and dewatering after the anaerobic treatment. Compared to dry processes, the need for pumping and transporting large volumes of suspended feedstock in wet processes consumes additional energy.

The processes' inherent heat demands are based on the maintenance of the mesophilic or thermophilic process temperatures and are accordingly accounted for in the calculations of the net heat yields. The heat demands of the different technologies and processes vary widely.

4.2 Net Electricity Production

The results for the net electricity yields demonstrate that consideration of the electricity and fuel consumption improves the values for the dry, notably dry discontinuous processes. On average, the highest net yields were achieved by dry continuous processes. In spite of their low inherent energy consumption, dry discontinuous processes, because of low methane yields, do not achieve the net electricity yields obtained by dry continuous processes.

Based on the collected data, wet processes have higher overall energy consumption (combined electricity and diesel fuel consumption), at 65 kWh per ton, compared to the dry continuous processes, at 48 kWh per ton. The dry discontinuous processes have the lowest overall energy consumption, at 36 kWh per ton.

Compared to the intensive wet and dry continuous processes, the low energy demand of the dry discontinuous processes is mainly attributable to the low need for intensive mechanical pretreatment of the feedstock prior to feeding. Energy is also saved because no dewatering after anaerobic treatment is required. The need to pump and transport large volumes of suspended feedstock into wet processes consumes additional energy compared to dry processes.

The results for the net electricity yields demonstrate that the consideration of the electricity and fuel consumption improves the values for the dry, notably dry discontinuous processes. On average, the highest net yields were achieved by dry continuous processes. In spite of their low inherent energy consumption, dry discontinuous processes do not achieve the net electricity yields obtained by dry continuous processes because of low methane yields. The data obtained in this study do not correspond to the findings of the Witzenhausen Institute [6], with mean values for dry, discontinuous and dry continuous processes of 230 and 250 kWh per ton, respectively. However, it has to be taken into consideration that the data of the Witzenhausen Institute refer to the input into the fermenter. Additionally, the authors considered higher specific biogas yields, with just below 100 Nm^3 per ton fermenter input, for discontinuous dry processes.

On average, the share of the electricity and diesel fuel consumption in the electricity produced from the wet processes was approximately 31%. The dry continuous and discontinuous processes are almost at the same level, at 22% and 24%, respectively (Fig. 5).

4.3 Net Heat Production

As expected, the wet processes have comparatively high heat demands due to the necessity of heating very large volumes of water-rich feedstock and the respective heat losses. Correspondingly, dry processes have lower heat demands. In discontinuous processes, no external heating of the feedstock is necessary because the heat is provided by the aerobic decomposition processes in the initial phase of the process. In the same way, some dry continuous processes use the heat produced

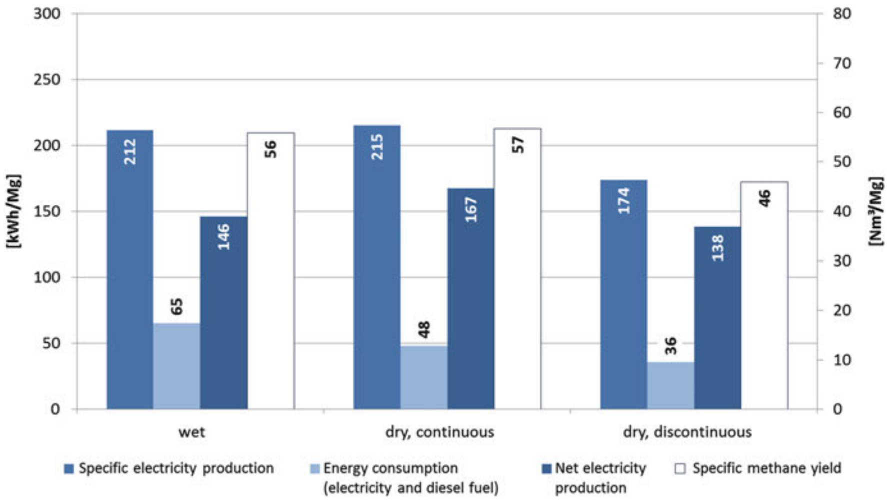

Fig. 5 Comparison of electricity production, consumption, and net electricity yields of wet and dry processes for anaerobic treatment of biowaste and green waste relative to the input into the facility

during short periods of aerobic pretreatment, usually 2–3 days, to heat up their feedstock.

Relative to the input into facilities, dry discontinuous processes have heat yields of 188–191 kWh per ton and therefore are almost on the same level with the dry continuous processes, with 173 and 191 per ton. The wet processes have heat yields of 153–204 per ton.

5 Measures for Improving Functionality and Energy Efficiency in the Anaerobic Treatment of Biowaste and Green Waste

The relevant measures include:

- Material flow management
- Technology and operation
- Biogas utilization
- Weak points

5.1 Technology and Operation

5.1.1 Pretreatment and Classification Before Anaerobic Treatment

The objective of the pretreatment of biowaste and green waste is to prepare the materials for the anaerobic treatment, as well as to discharge compounds that could compromise the process or the products. In the beginning of the anaerobic treatment of solids, such as biowaste and green waste, these were shredded to a size of <40 mm to improve the availability of organic compounds for the microorganisms and, therefore, a faster and more effective degradation of the feedstocks. In the past years, this kind of pretreatment was modified in the way that the feedstocks are shredded to a size according to the demands of the individual anaerobic processes, with grain sizes of 60–80 mm. Several facilities have since been modified accordingly, without perceivable reductions in biogas production.

In discontinuous dry processes, the waste is usually not pretreated, avoiding investment and operation costs for machinery. Furthermore, too small a grain size can impair the percolation through the piles and therefore reduce biogas production. At most dry discontinuous anaerobic treatment facilities, a wheel loader is used to mix the biowaste and green waste with digestion residues and to load the fermenters. Therefore, the feedstock is comparatively inhomogeneous, which can compromise the efficiency of the percolation process. The homogenization of feedstocks was analyzed within the scope of optimization measures at a discontinuous dry anaerobic treatment facility using a conventional mobile compost turner. The homogenization effect of a single turning process resulted in an impressively higher biogas production of 10%–15%. Equal homogenization effects can be expected by the upstream installation of a screen with grain sizes of 100–120 mm. Compared to plane sieves, drum screens result in better homogenization and, additionally, exert a shear force on the material.

If suitable green waste is to be treated anaerobically, specific logistics must be installed for separate collection, delivery, and stockpiling in order to classify the materials into batches appropriate for anaerobic treatment, composting, or energetic utilization. When mixed green waste is delivered together with tree and bush cuttings, a separate pretreatment step prior to the anaerobic stage is necessary. In these cases, shredding and mixing are helpful, because the oversize material appropriate for composting or energetic utilization accumulates at >80 mm, whereas fines of <80 mm constitute the material suitable for anaerobic treatment.

5.1.2 Loading of Fermenters

The efficiency of the anaerobic process can be increased by a continuous feeding regime of the anaerobic fermenter, resulting in stable biogas production with constant quality. Intermittent feeding only during the daylight hours and on working days results in fluctuations in biogas production. Especially during the night and on weekends, an impressive decrease in biogas production becomes apparent. Moreover, alterations in biogas quality have been observed just after feeding (decrease in methane content) and after longer periods without feeding (increase in methane content).

5.1.3 Process Temperature

Given the usual retention times, operation within the thermophilic temperature range results in an impressively higher biogas production of up to 15% and, consequently, in higher methane yields. Discontinuous dry and wet processes are mostly operated in the mesophilic range, whereas most of the continuous dry processes are operated in the thermophilic range. Therefore, the first group offers an especially high potential for optimization. The market development shows a tendency toward the thermophilic operation of anaerobic processes, and at several locations with dry discontinuous processes, while a transition to thermophilic operation is planned. According to several suppliers of corresponding facilities, the implementation of processes with thermophilic operation is planned for the majority of the facilities currently under construction. Besides the hygienization of the material, higher biogas yields are expected by thermophilic operation.

5.1.4 Dewatering

Unlike exclusively aerobic processes, anaerobic treatment processes for biowaste and green waste produce relevant volumes of process water. In terms of utilization, the biodigested residues, if hygienizated, are directly applied to agricultural areas or subjected to aerobic posttreatment for compost production. If aerobic posttreatment is planned, the residues have to be dewatered. This energy-consuming process stage is necessary for all continuous processes. Discontinuous processes usually do not need a dewatering step prior to aerobic posttreatment. The residues from the anaerobic treatment of bio- and green waste have to be dewatered to achieve a humidity of about 60%; when structural material is added, slightly higher humidity contents are acceptable. Anaerobic treatment facilities with continuous processes produce surplus water volumes per mass input of 200–500 L per ton. The dry discontinuous anaerobic treatment processes produce volumes of surplus water from the percolation of about 20–60 L per ton (Fig. 6).

Among the optimization potentials of the dewatering stage, the following measures are recommended:

- Reduce the required dewatering intensity by utilizing surplus heat for drying purposes during aerobic treatment.
- Intensify application of structural materials as long as there is no other more sustainable utilization for this material.

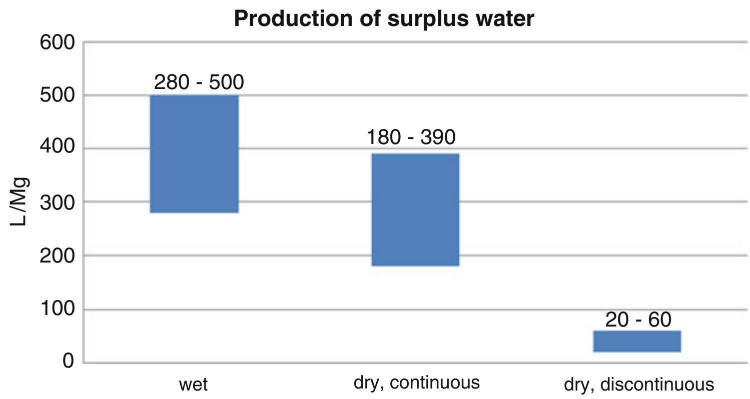

Fig. 6 Production of surplus water in the anaerobic treatment of biowaste and green waste according to technology and process type

- Hygienizate residues from the anaerobic stage and apply them directly to agricultural areas.

5.1.5 Data Availability for Energy Consumption

In none of the studied facilities were data available on the energy consumption of certain sectors or machines. Therefore, it was not possible to identify the energy conservation potentials of individual process stages.

5.2 Biogas Utilization

In more than 90% of the facilities, CHP units were in operation, and at least three of these installations also injected biogas into a microgas network, supplying gas to nearby CHP units connected to a heat distribution network or a heat consumer. The electric efficiencies were in the range of 32–42%, with a mean of 38%, and the mean thermal efficiency was 46%.

At almost 10% of the facilities, the biogas was upgraded to natural gas quality – biomethane – and fed into the public gas grid. An experimental fuel cell for biogas was installed at one facility. At another facility, the biogas was upgraded to fuel gas for garbage trucks. In 78 of the facilities, part of the surplus heat was used to heat fermenters and feedstock in order to adjust and maintain the necessary mesophilic or thermophilic temperatures. At least 17 facilities dry their digested residues or use the surplus heat-to-heat process air in order to control the composting process.

The electric efficiency of the CHP units has constantly increased during the past few years. CHP units in the range of about 500 kWh achieve efficiencies of 42%. Here, the optimization potential lies in the replacement of old units. However, as a result of increased electrical efficiencies, the thermal efficiencies of modern CHP units have decreased. The possible impacts on existing heat utilization concepts have to be assessed very critically. The corresponding thermal efficiencies are at 44%. The increased efficiency of CHP units translates into higher requirements being placed on biogas quality. In this regard, the removal of sulfur compounds has gained special importance.

5.3 *Weak Points*

The questionnaires and visits to the facilities focused on the weak points of the individual treatment stages, the machines, as well as of the whole system. The willingness of the facilities' operators to provide information varied widely, as was to be expected. While some of the interviewees were quite willing to provide information about problems encountered with technology, operation, or economic difficulties, the majority of the operators chose to limit their answers. The data collected during interviews and visits were complemented by interviews with suppliers and engineering companies, as well as by analyses of a number of litigated cases. All interviewees identified optimization potential, principally in terms of wear and tear and maintenance, but also relating to their facilities' processing capacities and ability to achieve higher efficiencies. Sedimentation and incrustation in the fermenter and dewatering processes were identified as principle areas for where wear and tear and the need for maintenance could be reduced. Problems with abrasion and corrosion were also reported frequently.

5.3.1 Sedimentation, Flotation, and Incrustation

Problems with sedimentation occur in both wet and dry continuous anaerobic processes. Frequently, sedimentation is accompanied by incrustation, intensifying the solidification of sediments. The effects on operation can be summed up as follows:

- Sedimentation, flotation, and incrustation:
  - Sediments and/or floating of particles in fermenter vessels reduce the available volume. In concrete cases, reductions of up to 40% have been observed.
  - Sediments combined with incrustation can compromise the mechanical equipment in the fermenter, such as mixers and cleaning devices, because they increase mechanical strain or render the whole system inoperable by blockage.
  - In horizontal fermenters with plug-flow technology, sediments can impede the material transport, resulting in shortcuts in material flow. In vertical fermenters, incrustation and blockage of the outlets can occur.
  - Blockage of pipes, various outlets, slide valves and vents, etc.
  - Blockage of fixed beds inhibits the proper flow within the reactor, causing malfunctions in the fixed bed.

- Signs of wear and tear:
  - Excessive signs of wear and tear, which culminate in deterioration, are caused by abrasion and are mainly seen in shredders, pumps, and mechanical dewatering devices.
  - Corrosion is promoted by abrasions.

The abovementioned problems can cause massive operational and economic damage that ranges from reduced performance to total failure of the facility. Fermenters may have to be shut down, opened, evacuated, repaired, and then started up again. When reserve capacities are not sufficiently dimensioned, downtimes of several months can be sustained. Downtimes are also caused by the need for frequent repairs. Further consequences are shorter lifetimes for equipment and components, different warranty periods offered in tenders and costs for maintenance, repair, and operations (MRO). Energy efficiency is compromised by restrictions on the facility's availability.

Approaches

The main approach for wet and dry processes is to minimize minerals and metal fractions prior to feeding the substrate into the fermenter.

Dry processes:

- Efficiently separate Fe and non-Fe metals and other heavy materials and floating particles like plastic and wood prior to feeding the substrate into the fermenter.
- Adjust feedstock viscosity within a narrow range. To minimize sedimentation and flotation, only a narrow viscosity range is available for process control, which does not impair effective pumping and mixing, while still inhibiting, respectively, fast floating particles from sinking too fast. This range has to be determined individually for each facility and feedstock to be processed.
- In order to prevent the formation of potential sedimentation zones, design the fermenter in such a way as to avoid dead zones, especially in vertical fermenters, and to opt for slopes that promote easy sediment discharge. Especially in the outflow area, the substrate needs to be discharged freely in order to purge the sediments from the fermenter and to avoid blockages.
- Depending on fermenter geometry, design suitable flushing and removal devices, if possible. Removal devices, such as push and scraper floors, need to be constructed on appropriate, i.e., abrasion resistant, surfaces, equipped with a sufficient number of hold-down clamps and mounted on stable guide rails. One supplier completely eliminated scraper floors from his portfolio. Sediments can be broken up by installing systems for the injection of pressurized gas or liquids.
- Given that the fermenters have to be opened or emptied, it is recommended to include reserve systems for the fermenters in the technical design to avoid the loss of the anaerobic stage with certainty. An appropriate inoculum is a prerequisite for a brief start-up of the inspected fermenter. However, this approach may not be suitable for smaller facilities due to economic aspects.

- Since maintenance of devices inside the fermenters is usually associated with the opening and emptying of the fermenters, the external assembly of drive systems is favorable.
- The installation of appropriate control systems for the monitoring of sediments and incrustations is recommended. Methods based on acoustic or infrared technology are still being tested and are not yet available as reliable monitoring tools.
- The warranty should define the lifetime of the fermenters until the first inspection or opening, and clarifying liability in case an inspection becomes necessary before the warranty expires.

Wet systems:

The authors possess detailed knowledge of the abovementioned area, resulting from the operation of wet fermenters with or without a fixed bed. The knowledge of fixed-bed reactors stems from residual waste treatment processes:

- Many of the abovementioned solutions are also valid for wet processes, in the same or slightly modified form, and will not be repeated here.
- With fixed-bed reactors (wet process), the solids in the effluent have to be limited to $<1\%$ of the fresh matter. In this way, the aforementioned problems with clogging and blockage of the fixed bed can largely be prevented. Even if incrustations cannot be totally avoided, a considerable part of the basic matrix is removed. With these low solid contents, sludge removal is less expensive, and the formation of floating layers is counteracted.
- The sole separation of heavy materials in the mixer of the pretreatment stage is judged not to be sufficient to counteract sedimentation problems. Generally, good separation results can be obtained with decanter centrifuges. Granular components can usually be removed with sand traps, but are not suitable for the efficient elimination of very fine sands and fibers, which is necessary for fixed-bed reactors. In wet fermenters without fixed beds, a sand trap is often installed after the mixer. Vibrating screens equipped with very fine mesh cloth are appropriate for the almost complete elimination of fibrous substances. However, this equipment is difficult to assess regarding their performance in removing fine sands.

5.3.2 Corrosion and Abrasion

Corrosion, principally of metallic materials, is predominantly observed on peripheral machinery at anaerobic treatment facilities, mostly on the equipment used in the posterior aerobic treatment stage. Damage due to corrosion results in higher expenditures for maintenance and repairs and shorter lifetimes while compromising the process, with the respective effects on operating costs and efficiencies [7]. Unfortunately, composting and anaerobic treatment facilities provide ideal environments for corrosion processes.

Approaches

- Use higher-quality materials for construction and equipment. Stainless steel is recommended for mechanically stressed metal parts, such as those affected by erosion and corrosion by abrasion; do note, however, that corrosion, like pitting, has also been observed in V2A and V4A steels.
- Substitute metal pipes with plastic or mineral-based products. In one case, due to massive corrosion, the replacement of $AlMg_3$ alloy pipes (suction aeration) with plastic pipes became necessary.
- Ensure corrosion protection via suitable coatings. Good experience has been had with three-layered coatings after sandblasting with 80 μm, epoxy zinc dust primer; middle layer, epoxy resin with micaceous Fe oxides; and top layer, polyurethane varnish.
- Improve insulation of process areas at increased corrosion risk from humidity, dust, and organic-rich atmosphere to separate them from other areas of the facility using constructive and process engineering concepts. If possible, relocate sensitive functional components to less corrosive environments.
- Some of the reported corrosion appeared in places damaged during assembly, which had not been sufficiently coated afterwards. These weak points that are never completely avoidable have to be localized and repaired as soon as possible.
- Intensify removal of biofilm deposits from surfaces.
- Establish sufficient air exchange rates in order to better remove warm air and humidity from the composting halls.
- Insulate and operate electric and control cabinets under positive pressure.
- Intensify monitoring of components susceptible to corrosion and protect, as well as immediate replace, damaged anticorrosion coatings.

6 Conclusions

The anaerobic treatment of biowaste and green waste in Germany has not gained the importance it deserves by far, owing to its ecological advantages. This is also evidenced by the high expansion and development potential afforded by the anaerobic treatment. There is a need for action in two areas: (1) increase the amount of biowaste collected by establishing a tightly meshed nationwide expansion of the organic waste bin system and increase the collection rates and (2) channel a large proportion of the biowaste currently only undergoing composting into fermentation as well. The potential for increasing fermentation in Germany is estimated at 5.4 million tons.

Fundamentally, the question must be discussed of whether it is imperative to collect kitchen and garden waste (biowaste) separately or whether it is also possible to sustainably utilize kitchen and garden fractions from mixed waste. Nevertheless, compost from separate collections continues to have significantly better quality than compost from mixed waste. An improvement in the concentrations of relevant heavy metals in compost generated from mixed waste, e.g., by MBT technologies, has been observed since the 1990s. This development is attributable to improvements in reprocessing and conversion technology and to a lower biowaste burden per se triggered by a decline in exhaust emissions. Comprehensive waste analyses are recommended before implementing measures for biowaste utilization that should not only be aimed at determining quantities but also at analyzing the gas potential, for example, and the burden from pollutants. This way, robust data on the sizing of biowaste plants can be provided. In certain regions, like predominantly rural areas, the use of efficient reprocessing and conversion technologies might generate similarly good compost qualities from mixed waste as those produced by complicated separately collected biowaste.

Relevant process technologies have undergone impressive advancements in the past few years. In the 1990s, the construction of wet processes prevailed, whereas almost exclusively dry single-step processes were run in the 2000s. This trend continues at facilities currently under construction. Among the reasons given for this trend in the survey were low investment costs, high operational stability, and user-friendliness. Given the lack of operational experience and sufficiently qualified personnel, the last point is of special importance.

Continuous dry processes have the highest mean net electricity yields. In spite of low intrinsic consumption, dry discontinuous processes do not come close to these yields. Wet processes do not yield higher biogas or methane quantities. Therefore, doubts arise as to whether the comparatively high technological and operational expenditure on the anaerobic treatment of solid waste from mixed waste is justified.

The possibilities for technological optimizations are manifold. In continuous dry processes, the necessity of intensive shredding has to be evaluated in order to find a way to reduce energy demand. In discontinuous processes, better homogenization can result in higher biogas yields. The separation of sedimentable compounds reduces the risk of sediment formation in the fermenter and lessens abrasion or wear and tear in downstream devices – a factor of major importance in the treatment of mixed waste. The formation of floating layers should also be avoided, especially in wet processes.

Thermophilic operations in all processes generate higher yields of biogas (up to 15%) and methane.Most discontinuous dry and wet processes operate within the mesophilic range and therefore hold comparatively high optimization potential. The development of CHP technology has improved electrical efficiency, which can be exploited in new installations and when replacing old units. The available options for gas utilization are currently only applied to a very limited degree. The utilization of process heat still holds an especially high optimization potential.

The dewatering stage ranks as the largest energy consumer. The utilization of surplus heat to control downstream aerobic treatment processes makes material composting with higher water content possible and reduces process water quantities. Positive effects are also expected to prevent wear to dewatering devices, as well as reduce energy consumption. The hygienization of the substrate prior to or during the anaerobic process offers the possibility of direct application onto agricultural fields, at least during the vegetation period. This option holds high optimization potential to increase energy efficiency.

Operational optimization can also be achieved by more regular feeding, including night and weekend shifts where special attention should be given to the management of the stockpiled feedstock. Furthermore, the appropriate maintenance extends equipment lifetimes and saves energy. For example, regular maintenance of the motors reduces the rate of mechanical losses and can yield energy savings of 3%–10%.

The measures described for sedimentation prevention and flotation in the fermenters should be implemented to guarantee a high availability of facilities. Monitoring devices should be installed.

Optimization approaches have been quantified based on the options described for the optimization of energy yields. Such approaches will increase the factors for electricity and thermal energy yields by at least 1.4 and 1.2, respectively [8].

Exploitation of optimization potential will be decisive for increasing efficiencies. Dry discontinuous processes have only been in operation on an industrial scale since 2006. Unlike the continuous processes used on an industrial scale since the mid-1990s, the potential to develop discontinuous processes is estimated to be comparatively high.

References

1. EEG (2012) Erneuerbare-Energien-Gesetz vom 25. Oktober 2008 (BGBl. I p. 2074), zuletzt geändert durch Artikel 1 des Gesetzes zur Änderung des Rechtsrahmens für Strom aus solarer Strahlungsenergie und zu weiteren Änderungen im Recht der erneuerbaren Energien vom 17. August 2012 (BGBl. I p. 1754)
2. Anonymous (2012) Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträglichen Bewirtschaftung von Abfällen (Kreislaufwirtschaftsgesetz – KrWG) vom 24. February 2012, BGBl. I p. 212
3. JRC-IPTS (2012) Biodegradable waste subject to biological treatment Third Working Document, August 2012, Seville (E)
4. Fricke K, Turk T, Vogtmann H (1991) Compost quality, physical characteristics, nutrient content, heavy metals and organic chemicals. In: Toxicological and environmental chemistry, 1993, vol 39. Gordon and Breach Science Publishers S. A, London, pp. 95–114
5. Fricke K, Heußner C, Hüttner A, Turk Th, Bidlingmaier W (2014) Steigerung der Energieeffizienz bei der Vergärung fester biogener Reststoffe. In: Thrän D, Pfeiffer D (eds), Schriftenreihe des BMU-Förderprogramms. Energetische Biomassenutzung, vol 11. Erich Schmidt Verlag, Berlin
6. Witzenhausen-Institute (2010) Aufwand und Nutzen einer optimierten Bioabfallverwertung hinsichtlich Energieeffizienz. Klima- und Ressourcenschutz, Umweltbundesamt, Dessau
7. Fricke K, Thiel T, Ketelsen K, Bahr T, Wallmann R, Turk T (2009) Korrosion bei biologischen Abfallbehandlungsanlagen. In: Müll und Abfall 11. Erich-Schmidt-Verlag, Berlin
8. BMU (2013) Steigerung der Energieeffizienz in der Verwertung biogener Reststoffe, Förderprojekt des BMU, 03KB022. TU Braunschweig, Bauhaus Universität Weimar und Fraunhofer UMSICHT, Berlin

The Effect of Source Separation on the Waste Disposal Process: Case Study in Hangzhou

Yuyang Long and Dongsheng Shen

Abstract MSW source separation is a key procedure for its later processing. Kitchen waste, the main contributor to moisture content, accounts for a very high proportion (~60%) in MSW composition. The feasible way to dispose of MSW before or after separation depends on the reasonable disposal of kitchen waste. Here, a case study from Hangzhou, China, is presented in terms of the source separation effect on the waste disposal process. In Hangzhou, three strategies, including direct digestion without separation, composting after separation, and co-digestion with fruit and vegetable waste, were explored. It indicates that:

1. MSW digestion without separation is a possible means of refuse disposal. The refuse and leachate in the reactor connected with the aged refuse column and reached a strongly degraded and more stable state compared with directly recycled leachate.
2. Kitchen waste composting after source separation is a better choice. However, the high water content is the key issue that needs attention. Especially, the water state should be paid more attention to. Additives like PAM can significantly enhance the capillary force and delay the decrease in moisture content during aerobic decomposition and improve the composting process.
3. Kitchen waste co-digestion with fruit and vegetable waste has a high application potential. The two-phase AD with 50% kitchen waste was a reasonable ratio in this two-phase AD system.

Keywords Co-digestion, Composting, Digestion, Kitchen waste

Y. Long and D. Shen (✉)
Zhejiang Provincial Key Laboratory of Solid Waste Treatment and Recycling, School of Environmental Science and Engineering, Zhejiang Gongshang University, Hangzhou 310012, China
e-mail: longyy@zjgsu.edu.cn; shends@zju.edu.cn

R. Maletz et al. (eds.), *Source Separation and Recycling*, 199
Hdb Env Chem (2018) 63: 199–226, DOI 10.1007/698_2017_31,
© Springer International Publishing AG 2017, Published online: 31 May 2017

Contents

Abbreviations

AD	Anaerobic digestion
APR	Acidogenic phase reactor
COD	Chemical oxygen demand
CW	The water removed at 60 and 70°C
EC	Electrical conductivity
EW	The water removed at 30, 40, and 50°C
FVW	Fruit–vegetable waste
HRT	Hydraulic retention time
KW	Kitchen waste
MMLW	The water removed at 80, 90, 100, and 105°C
MPR	Methanogenic phase reactor
MSW	Municipal solid waste
NDF	Neutral detergent fiber
NDS	Neutral detergent solute
PAM	Polyacrylamide
TN	Total nitrogen
TS	Total solids
VFA	Volatile fatty acids
VRR	Volume reduction rate
VS	Volatile solid
WHCs	Water holding capacities

1 Introduction

MSW relates to a broad array of issues, such as social, economic, environmental, technological, and legislative and is regarded as unwanted materials to be disposed of. Currently, the world generates approximately 1.3 billion tons of MSW per year, which is expected to increase to 2.2 billion tons by 2025 [1]. Waste separation at the source is subjectively done by individuals collecting recyclable or compostable materials from commingled waste and placing it at disposal locations at their homes for collection. The main purposes of source separation are recycling, reuse, and reducing environmental as well as economic burdens to the MSW management systems. The major impact on the effectiveness of MSW management systems comes from the separation of waste causing essential changes in the quantity and quality of waste reaching the final management process, or waste treatment and disposal [1].

Hangzhou, located along the southeastern coast of China, is the capital of Zhejiang Province. The total area of the city covers 16,596 km^2 with a population of 8,892,000. It is a key central city in the Yangtze River Delta and a traffic hub in southeastern China. Hangzhou is in a subtropical zone with a monsoon climate. The annual MSW output of Hangzhou was 3.65 million tons in 2015. From the MSW source separation guidelines in Hangzhou, MSW must be separated into at least four fractions. The Department of Urban Appearance and Environmental Renovation guides the MW classification based on the principle of easy reduction, recycling, identification, and classification. The standard of classification of MSW in rural areas could be appropriately adjusted to combine with the actual local situation (Fig. 1).

1. Recoverable matter is a component of unpolluted MSW suitable for recycling and reutilization, such as paper, plastic, glass and metal, etc.
2. Hazardous waste is a component of MSW, which can cause direct or potential hazards to human health or the environment. This includes waste rechargeable batteries, waste button cells, waste fluorescent lamps, waste medicines, waste pesticides, waste paint, daily chemical waste, waste mercury products, etc.
3. Food waste, which is produced during the process of production by restaurant operators, unit dining rooms, etc. This also includes food waste from families' everyday life and putrescible wastes from the market, as they all belong to the refuse.

Fig. 1 MSW source separation categories in Hangzhou

4. Other wastes not allocated to fractions for recoverable substances include hazardous waste and food waste. These are mixed, soiled, and difficult to classify, in contrast to paper, plastics, glass, metals, fabrics and wood, etc.

2 The Effect of Source Separation on Waste Disposal Processing

Kitchen waste accounts for a very high proportion (~60%) of MSW composition in Hangzhou. Moreover, it is also the main contributor to the moisture content. Therefore, the feasible way to dispose of MSW before or after separation depends on the reasonable disposal of kitchen waste. Three strategies, including direct digestion without separation, composting after separation, and co-digestion with fruit and vegetable waste, were explored. Here, the main processes and results are presented.

2.1 MSW Digestion Without Separation

2.1.1 Research Setup

For this processing, the results of pilot scale research are shown. Two digestion systems were designed and operated (Fig. 2), namely, system I and system II. System I comprised only waste column R1 loaded with fresh refuse, from which the leachate was collected by tank J1, and then directly recycled using a pump for nearly 16 h every week. System II was a sequencing batch reactor, which was comprised of waste column R2 loaded with fresh refuse and R3 loaded with 1 year of aged refuse. The leachate generated from columns R2 and R3 was first drained into recirculation tanks J2 and J3, respectively, and in the meantime, R2 and R3 were fed with the leachate from tanks J3 and J2, respectively, by pump for nearly 16 h every week. Three waste columns were constructed with the same size and materials with a thickness of 5 cm, an internal diameter of 1,400 mm, and a height of 2,000 mm. All of the reactors were placed in an outdoor venue of Hangzhou and operated for 20 weeks during the experiment.

2.1.2 MSW Composition and Operation

The MSW used was not separated. Columns R1 and R2 were packed with 1,600 kg of fresh refuse collected from Hangzhou at a wet density of 700 kg m^{-3}, respectively, and the average composition was (by wet weight, w/w) 63.12% kitchen residue, 12.81% slag, 8.93% paper, 2.54% glass, 8.38% plastics, 0.11% metal, 1.15% cellulose textile, 1.95% stone and brick, and 1.01% other. The initial

Fig. 2 Setup of tested systems

characteristics of the fresh refuse were 710 mg kg^{-1} TN (dry refuse), 62.72% VS (w/w), 50.97% biodegradable matter (w/w), 6.98 pH, and 60.73% moisture content.

2.1.3 Results

Settlement of Refuse in Three Waste Columns

VRR data for the refuse of reactors R1, R2, and R3 are presented in Fig. 3a. As illustrated, the settlement of refuse in the three columns mainly took place in the first 20 days. The VRR showed a similar trend in two fresh refuse columns, columns R1 and R2, both of which increased linearly up to 20% after the experiment had been started for 2 days, then their VRR increased slowly with different rates, and column R2 connected with aged refuse column R3 and showed a more rapid rate than column R1, though both of them maintained approximately 50% and 44% after 40 days, respectively. No significant change in VRR was detected in the old waste column, R3. Only a small increase in VRR was observed, which stagnated at 7% after 7 days. This indicates a substantial stabilization of the decline in R3.

Characteristics of Leachate VFA and pH

VFA are the most important intermediates in the anaerobic digestion process, and there is a close relationship between VFA concentration and pH value. Therefore,

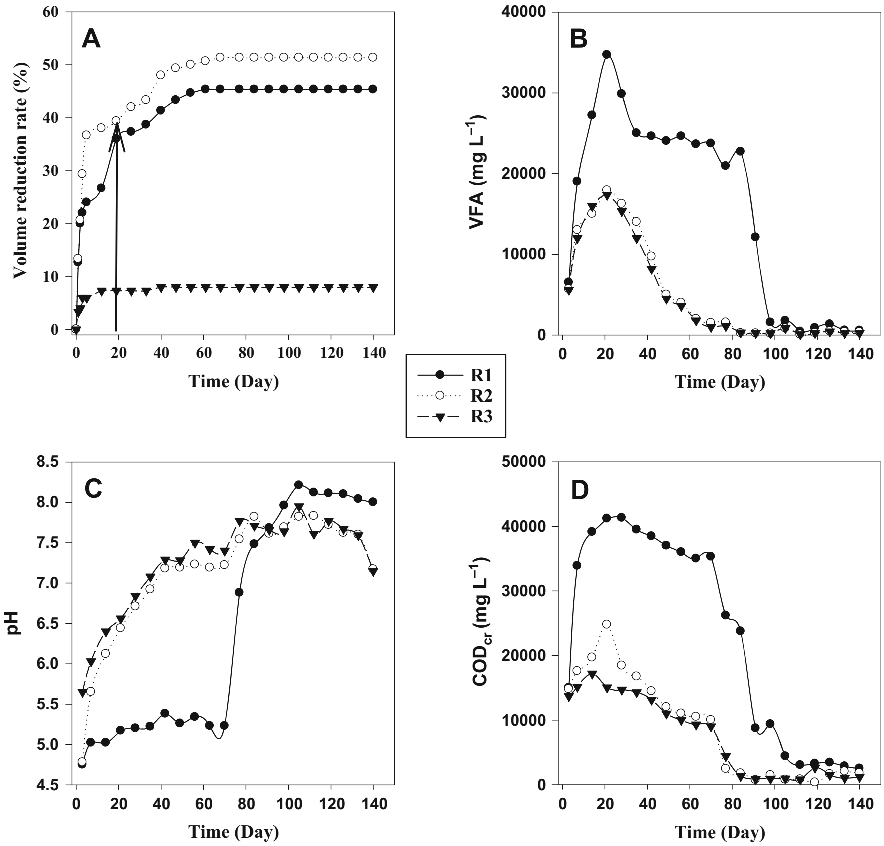

Fig. 3 Time evolutions of VVR (**a**) for refuse, VFA (**b**), pH (**c**) and COD (**d**) in leachate during operation

VFA have been monitored for a long time as process performance indicators [2]. As can be seen from Fig. 3b, the VFA concentration presented the same trend in the leachate from reactors R2 and R3, both of which increased slowly at the beginning of the 21 days, and reached maximum values of 17,932 and 17,369 mg L^{-1}, respectively. Then from day 28, the leachate concentration of VFA began to decrease slowly and finally maintained around 350 and 250 mg L^{-1}, respectively. However, the leachate VFA concentrations increased linearly at the beginning of 21 days for reactor R1 and reached maximum value of 34,680 mg L^{-1} on day 21, which is nearly two times higher than the leachate VFA concentration of reactor R2. From then on, the VFA concentration presented a different trend. It first decreased to 25,000 mg L^{-1} on day 35, and then no considerable change was observed during the succeeding 49 days. Afterwards, the leachate VFA concentration for reactor R2 decreased rapidly and was finally maintained at approximately 550 mg L^{-1}. The rapid increase of VFA in landfill reactors R1 and R2 was attributed to the accumulation of soluble long-chain fatty acids in the leachate. As known to all, acidogens are fast-growing bacteria with a minimum doubling time of around 30 min, and then most of the soluble organic refuse was converted to VFA in a short time interval. As a result, the leachate VFA concentration reached its peak value within 21 days. However, reactor R2 was connected with aged refuse reactor R3, and the VFA produced by reactor R2 was neutralized by the leachate from the aged refuse reactor, which showed the advantage of the two-phase processes for higher bioconversion efficiency and system stability compared to the directly recirculated reactor. Therefore, although reactors R1 and R2 were loaded with the same refuse, the peak and average value or time span of the high concentration of VFA in reactor R2 was lower or shorter than that in reactor R1.

The pH values were in accordance with the concentration of VFA monitored for all three reactors. Leachate pH values of reactors R2 and R3 increased after the experiment started and reached 7.18 and 7.29 on day 42, respectively, and then stayed within the range of 7.19–8.04 in the succeeding 98 days, indicating that reactor R2 had already transferred from the acid phase to the methane fermentation phase. On the contrary, an ensiling problem was observed in landfill reactor R1, no considerable variation was observed in the leachate from this reactor, and the pH values remained in the range of 4.75–5.38 in the first 10 weeks due to the accumulation of VFA (Fig. 3c). After day 70, the leachate pH values began to increase and reached 8 after day 105 in reactor R1. After that, no significant variation was observed and was measured between 7.78 and 8.21. Low pH values observed at the early stage in reactor R1 may be ascribed to the production of low alkalinity in reactor R1, which is not enough for maintaining the neutral pH and buffering the VFA produced [3, 4]. The sudden increase on day 77 for reactor R1 might have resulted from the hydrolyzing and fermentation of VFA to carbon dioxide and methane, which agreed with the decrease in the leachate VFA concentration. These results indicated that the fresh refuse reactor connected with the aged refuse column was beneficial to reaching a strongly degraded and more stable state compared with directly recycled leachate.

Characteristics of Leachate COD

As was shown in Fig. 3d, due to the rapid release and hydrolysis of polymers such as carbohydrates, fats, and proteins from the fresh refuse into the leachate, COD concentrations increased from 15,000 and 14,800 mg $L^{-1}$to maximum values of 41,184 and 24,770 mg L^{-1} for reactors R1 and R2 after 21 days of operation, respectively. After reaching maximum values, the leachate COD concentrations for reactor R2 decreased slowly and maintained at 10,000 mg L^{-1} on day 70. Afterwards, the concentration began to decrease rapidly and maintained around 1,778 mg L^{-1}. However, no significant change was observed in the leachate COD concentrations for reactor R1 from days 22 to 70, which is in accordance with the progression law of VFA and low pH value attained from the former elucidation. Thus, the long stage for a high level of COD from reactor R1 might be attributed to the low activity of methanogenic bacteria, which only grow within a narrow pH range around neutrality [5]. Afterwards, with the decrease of VFA concentration and increase in pH value, COD concentrations began to decrease rapidly for reactor R1, and the concentration on days 91–140 were determined to be 8,720–2,500 mg L^{-1}. As for reactor R3, the leachate COD concentrations increased slightly during the first 2 weeks, and then decreased gradually to 9,000 mg L^{-1}. Afterwards, the concentration began to decrease rapidly and maintained at around 1,185 mg L^{-1}. Therefore, the combination with an aged refuse reactor not only had a beneficial effect on the stabilization of fresh refuse but also on the degradation of leachate organic constituents, such as VFA and COD. The main reason for that might be the high microbial ability in aged refuse.

Characteristics of Leachate Nitrogen

The ammonia was always the major contributor to the overall nitrogen in the leachate as a result of the decomposition of organic matter containing nitrogen, such as protein and amino acids. The long-term, high-concentration ammonia accumulation was observed in the leachate from reactor R1 as reported by [5–7], and this phenomenon often occurred in the anaerobic bioreactor landfill. As was shown by Fig. 4a, the leachate NH_4^+-N concentrations for reactor R1 started to increase quickly and accumulated to more than 2,000 mg L^{-1} within the first 28 days. After a stabilized period of 42 days, the leachate NH_4^+-N concentrations started to decrease and reached 1,658 mg L^{-1} on day 91. After that, no significant change was found, and the leachate NH_4^+-N concentrations were maintained at approximately 1,400 mg L^{-1}. The results of the present study are similar to those of [2, 8] and clearly showed that there is no mechanism for NH_4^+-N elimination in anaerobic landfills [9]. Nevertheless, the NH_4^+-N curves for reactors R2 and R3 presented a distinct trend, both of which increased slowly at the beginning of the

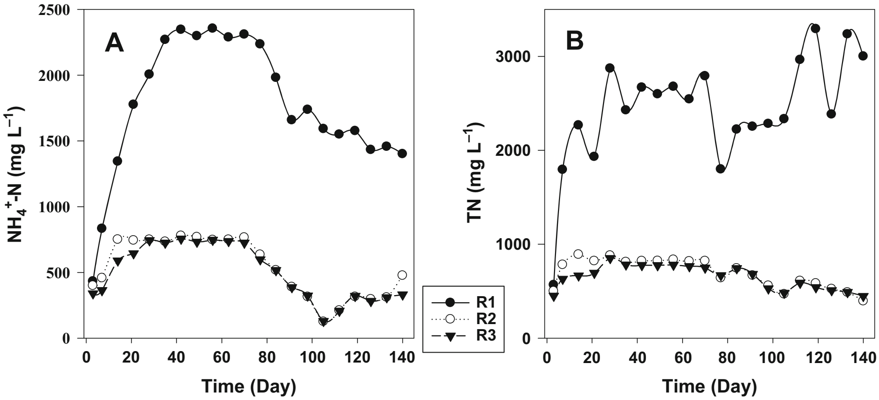

Fig. 4 Time evolutions of NH_4^+-N (**a**) and TN (**b**) in leachate during operation

28 days, and reached maximum values of 750 and 744 mg L^{-1}, respectively. Afterwards, no significant change was found during the succeeding 8 weeks, and the leachate NH_4^+-N concentrations for reactors R2 and R3 started to decrease gradually and the concentrations were determined to be 125–500 mg L^{-1}. The different NH_4^+-N concentration behavior among the two reactors, R1 and R2, might be attributed to the leachate recirculation management strategy, although these two reactors were loaded with the same refuse, which was in accordance with previous research [2]. As aged waste has a smaller particle size and thus a larger surface area, yielding more available reactive sites for sorption, the NH_4^+-N released from reactor R2 was removed by the adsorption of well-decomposed refuse in R3. On the contrary, as younger waste does not have enough potential for sorption, most of the NH_4^+-N generated from reactor D3 accumulated in the leachate. In the later period, the NH_4^+-N concentration in the leachate of reactor R1 decreased, which might have resulted from the formation of free ammonia from ammonium ions due to the increased pH and temperature, which was in accordance with previous research [10].

The TN values were in accordance with the concentration of NH_4^+-N monitored for both reactors (Fig. 4b). The leachate TN concentrations for reactor R1 increased quickly and accumulated to more than 2,871 mg L^{-1} within the first 28 days. After two stabilized periods (more than 70 days), the leachate TN concentrations started to increase again and reached 3,290 mg L^{-1} on day 119. After that, the leachate TN concentrations maintained approximately at 3,200 mg L^{-1} with a little fluctuation on day 126. However, the leachate TN concentrations for reactors R2 and R3 showed a significant trend, which was also in accordance with the change in leachate NH_4^+-N concentration. The leachate TN concentrations for both reactors increased slowly at the beginning of 28 days and reached the maximum values of 881 and 852 mg L^{-1}, respectively. Afterwards, no significant change was found during the succeeding 6 weeks. From day 70, the leachate NH_4^+-N concentrations for reactors R2 and R3 started to decrease gradually and finally stabilized at around 447 and 390 mg L^{-1}. Above all, the combined system of fresh and aged refuse reactor not only had a positive effect on the stabilization of fresh refuse but also on the degradation of leachate.

2.1.4 Summary

After 140 days of digestion, the refuse and leachate in the reactor connected with the aged refuse column reached a strongly degraded and more stable state compared with directly recycled leachate. The key constituents in the leachate, such as COD, NH_4^+-N, and TN, were able to meet the related discharge criteria.

2.2 KW Composting After Source Separation

KW in Hangzhou after source separation shows a special feature. As shown in Fig. 5, the moisture content of separated KW was always higher than 80%. Obviously, it is not feasible to compost before dewatering. The relatively low pH (5.0–6.0) may be caused by the partial AD during the dumping. It indicates that the KW has high biotransformation potential. Based on those basic characteristics of the KW after separation, dewatering should be taken into consideration during composting. Therefore, the cases of water state adjusting coupled with kitchen waste composting are presented.

In order to evaluate the moisture content adjusting effect, the water states were analyzed using a gradient evaporation technique. About 10 g of a finely chopped sample were spread uniformly on a glass tray (90 mm in diameter), and the tray was placed in an electrically heated air blast dryer (GZX-9076; MBE, Shanghai, China). The analysis was performed in stages at 30, 40, 50, 60, 70, 80, 90, 100, and 105°C. A residence time of 1 h was used at each temperature except for 105°C, and the time at 105°C was 2 h. After the residence time had been reached at each temperature stage, the temperature was increased to the next test temperature. The mass of each sample was carefully measured before and after drying at each temperature. The water removed at 30, 40, and 50°C was classed as EW; the water removed at 60 and 70°C was classed as CW; and the water removed at 80, 90, 100, and 105°C was classed as MMLW (Fig. 6). The water removed throughout the whole-gradient evaporation test was used to calculate the moisture content of the sample (Table 1).

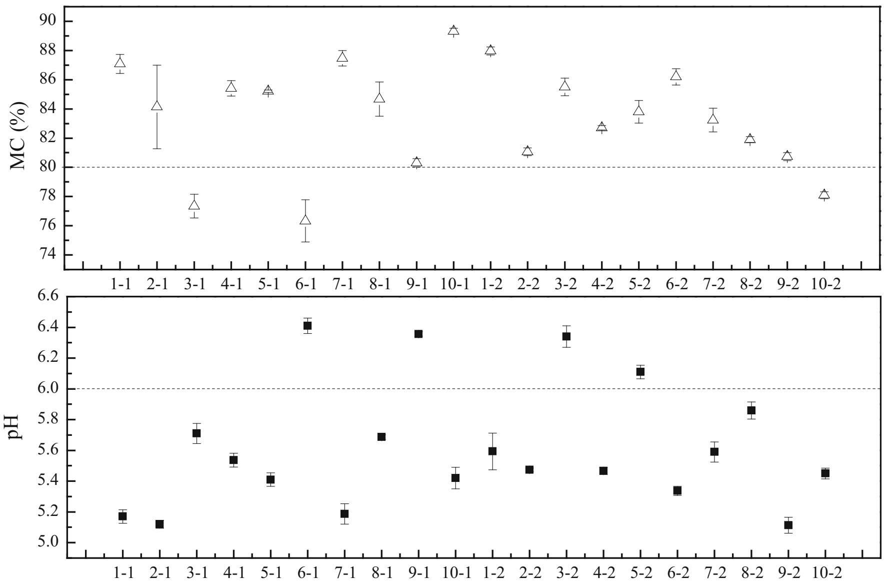

Fig. 5 Characterization of separated KW based on a 10-month survey in Hangzhou

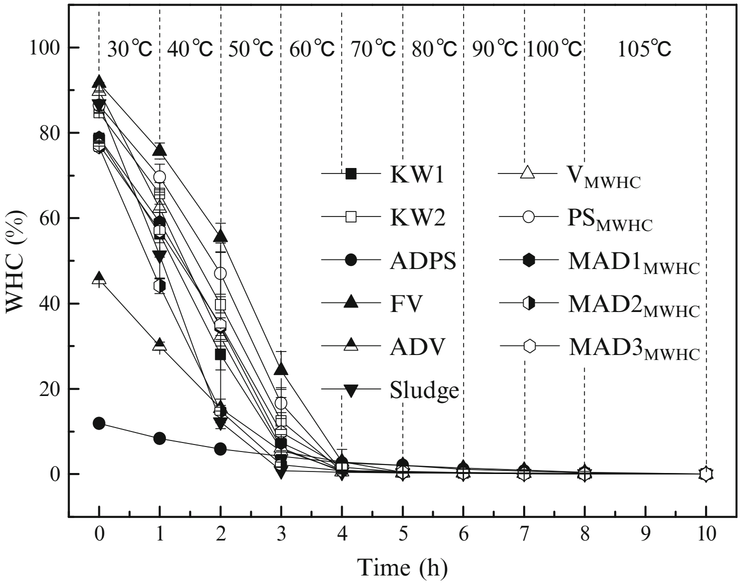

Fig. 6 WHCs of the samples during the gradient temperature test. The WHC at 0 h is the initial WHC of the sample; and the WHCs at 1, 2, 3, 4, 5, 6, 7, 8, and 10 h are the WHCs of the sample after it had been dried at 30, 40, 50, 60, 70, 80, 90, 100, and 105°C, respectively

Table 1 Statistical results for the linear models for each heating stage

Sample name	Stage 1 (room temperature, 30, 40, 50°C)		Stage 2 (60, 70°C)		Stage 3 (80, 90, 100, 105°C)	
	R^2	P	R^2	P	R^2	P
KW1	0.997	0.001	0.536	0.320	0.947	0.003
KW2	0.990	0.003	0.544	0.317	0.931	0.005
ADPS	0.963	0.012	0.870	0.164	0.932	0.005
PS_{MWHC}	0.974	0.009	0.539	0.319	0.972	0.001
FV	0.964	0.012	0.652	0.274	0.993	1.616×10^{-4}
ADV	0.986	0.005	0.824	0.192	0.991	2.231×10^{-4}
V_{MWHC}	0.999	3.850×10^{-4}	0.557	0.312	0.968	0.002
Sludge	0.937	0.021	0.853	0.175	0.991	2.188×10^{-4}
$MC1_{MWHC}$	0.993	0.002	0.608	0.292	0.982	6.487×10^{-4}
$MC2_{MWHC}$	0.951	0.017	0.789	0.211	0.912	0.007
$MC3_{MWHC}$	0.996	0.001	0.691	0.257	0.911	0.007

2.2.1 Using PAM for Water State Adjusting During the Composting

Materials and Methods

The raw material was fresh KW and air-dried garbage. The air-dried garbage was prepared from fresh garbage that was generated in food pretreatment processes, and it was used as a bulking agent for the composting system. All of the fresh KW and garbage was cut into pieces with diameters of 5.0 ± 0.5 cm. The cut fresh garbage was naturally air-dried for about 7 days to allow the excess water to evaporate, and then the air-dried garbage had been stored in an airtight plastic bag before use. The moisture content of the fresh KW and the air-dried garbage was 73.2% and 12.1%, respectively. PAM with a molecular weight of 3.0×10^6 Da was used. High-performance mixed flora, acclimatized and isolated from our previous work [11] and preserved at below −80°C in glycerol, was used as inoculums for the composting experiments. The flora contained microorganisms that could decompose starch, glucose, and protein. Before inoculation, the high-performance mixed flora was activated in a Luria-Bertani culture medium [12]. The concentration of the high-performance mixed flora seed that was used was higher than 1×10^{15} CFU mL^{-1}.

A laboratory-scale reactor with an effective volume of 16 L was developed for this composting trial (Fig. 7). The reactor consisted of an insulated cylindrical vessel, an air pump, a gas rotameter, and a temperature recorder with a thermometer probe. The vessel was made of plastic, and it was surrounded by a layer of rubber insulation board (20 mm thick) and covered with an insulating layer of straw (50 ± 5 mm thick). The thermometer probe was mounted in the center of the

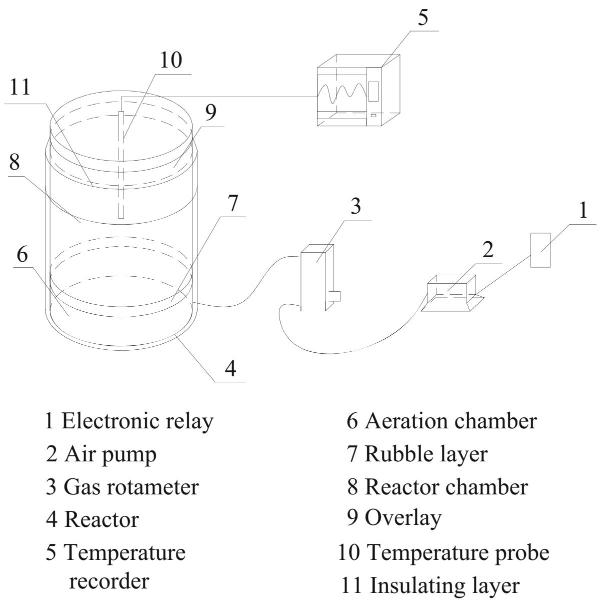

Fig. 7 The composting setup tested [13]

Table 2 The chemical characteristics of the mixture

Parameter	Value	Parameter	Value
Moisture content (%)	60.30 ± 0.90	NDS (%)	73.75 ± 1.67
C/N	26.55 ± 0.95	Hemicellulose (%)	14.89 ± 1.38
pH	4.92 ± 0.07	Cellulose (%)	6.95 ± 0.74
EC (mS cm^{-1})	1.99 ± 0.12	Lignin (%)	4.08 ± 0.63

composting pile, and the temperature was recorded once every 20 s. An aeration chamber was installed at the bottom of the vessel to maintain aerobic conditions, and the airflow rate was continuously controlled using a gas rotameter.

Four composting treatments, each with an initial moisture content of 60%, were used. The chemical characteristics of the mixture are shown in Table 2. To each system, 1 mL/kg of the high-performance mixed plant inoculum was added to the waste material. PAM was introduced into the four treatments at different times. R1 had 0.1% PAM added before the start of the composting process (day 0). R2 had 0.1% PAM added when composting stabilized in the thermophilic phase (at >50°C) (day 3). R3 had 0.1% PAM added when the moisture content had decreased significantly (day 7), and R4 had no PAM added. All four treatments were performed in a greenhouse (at 29 ± 1°C), the aeration rate in each was 0.8 L min^{-1}, and all four treatments had three replications at the same time.

Results

Temperature and Moisture Content

Temperature variations in all of the treatments are shown in Fig. 8a. The temperature followed a three-phase pattern in all of the treatments, and this pattern had a mesophilic phase, a thermophilic phase, and a curing phase. In the mesophilic phase (days 0–3), R1 had the highest temperature (>50°C), and this suggests that the PAM decreased the number of air-filled pores in R1, and that less heat was removed by the flowing air. In the thermophilic phase, the peak temperature was lower in R1 than in R2 and R3. The lower number of air-filled pores in R1 caused poor oxygen supply and less heat being produced in the composting system.

In the thermophilic phase (days 3–11), the peak temperatures in R1, R2, R3, and R4 were 57.8, 60.2, 63.9, and 57.8°C, respectively. There was a temperature increase in R2 and R3 after the PAM was added, and R2 remained at high moisture content between days 0 and 8 (Fig. 8b). The moisture content of R3 was higher on day 8 than on day 6. PAM can delay the decrease in moisture content, and that maintaining suitable moisture content could increase the level of microbial activity. Correspondingly, it also causes the accumulation of heat and the rise in temperature in the composting system.

The moisture content for all of the treatments throughout the 16 days experiments is shown in Fig. 8b. The moisture content in R3 and R4 had decreased

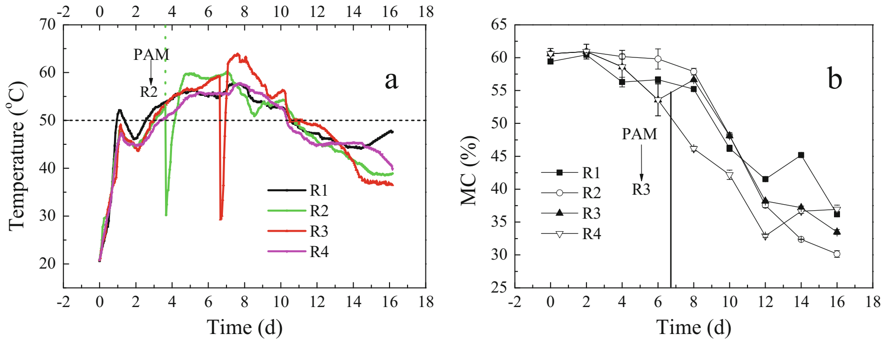

Fig. 8 Temperature (**a**) and moisture content (**b**) in the KW composting process

significantly by day 6, and the moisture content in these treatments was significantly lower than the moisture content in R1 and R2 on day 6, so 0.1% PAM was added to R3 to suppress the decrease in moisture content on that day. The changes in the moisture content in all of the treatments showed that PAM could improve the water holding capacity of the composting system.

As Fig. 9 shows, there were no visible differences in the MMLW values among the treatments, and the percentage of MMLW in all of the treatments fluctuated within a small range (3.9 ± 1.4%). This indicates that 0.1% PAM did not have any effect on the MMLW, and that the MMLW had no effect on variations in the moisture content in the composting systems. Changes in the water states mainly occurred in the EW and CW. The changes in the water states in all of the treatments followed similar trends, the percentage of EW followed an upward trend and the percentage of CW followed a downward trend, although the rate of change in the water states was different in each composting system (Fig. 9). For most of the time, the percentage of CW was higher in R1 and R2 than in R4 (Fig. 9a, b), and meanwhile the moisture content was higher in R1 and R2 than in R4 (Fig. 8b), which suggests that PAM improved the capillary force and retarded the processes that changed CW into EW in the composting systems and restrained the decrease in moisture content. There were no significant differences in the percentage of CW values in R3 and R4 (Fig. 9c), which may have been caused by the moisture content in R3 being relatively low (53.6 ± 2.6%) when the PAM was added to R3, meaning that less water could combine with the PAM in R3 than in R1 and R2. This indicates that the PAM should be added to the composting system when the moisture content in the composting system has not decreased significantly. The water states in R1 fluctuated between days 0 and 8, suggesting that the water had not been completely dispersed in the composting system when the PAM was added to R1.

pH and Electrical Conductivity

The changes in the pH found in each of the treatments are shown in Fig. 10a, and it can be seen that all of the treatments showed similar trends. At the beginning of the

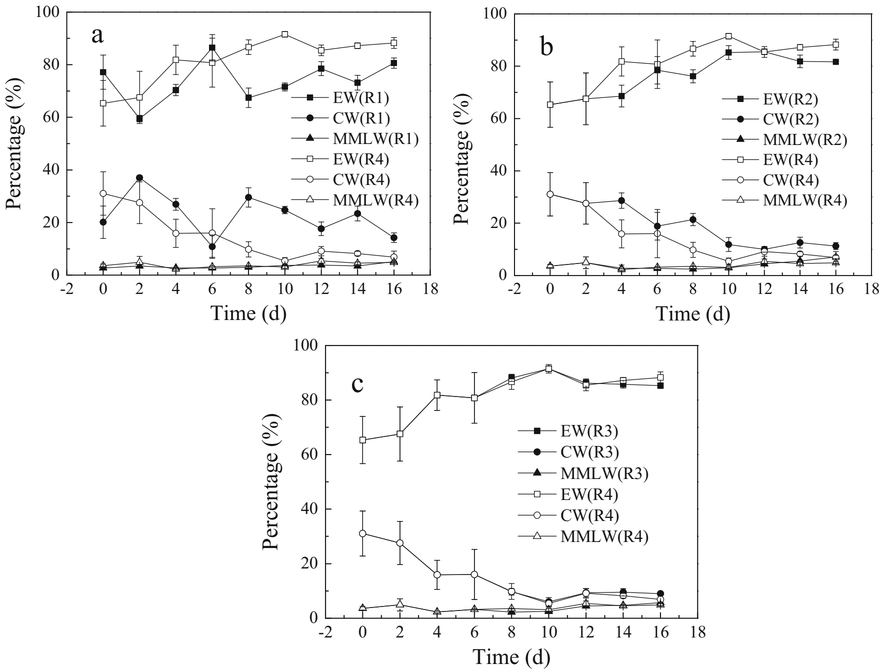

Fig. 9 Variation of water states (EW, CW, and MMLW) in the composting process

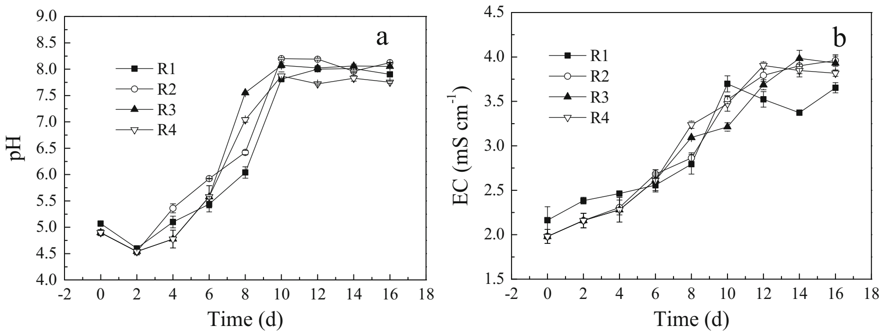

Fig. 10 pH (**a**) and EC (**b**) in the kitchen waste composting process

composting process, the kitchen waste was hydrolyzed very rapidly, and on day 2, the pH in all of the treatments had reached a minimum value (4.6 ± 0.1), coinciding with a downward trend in the temperature in the composting systems. On day 8, the pH values were lower in R1 and R2 than in R3 and R4, and this may have been caused by the moisture content in R1 and R2 still being high (59.8 ± 0.4%) when the PAM was added to them, so more water was absorbed by the PAM. The PAM in those cases may have acted as a bridge between the kitchen waste particles [14], making the KW particles agglomerate together, causing there to be less air-filled pores in R1 and R2 than in R3 and R4, and a higher percentage of CW values in R1 and R2 than in R3 and R4. This indicated that the mass transfer of water and air was inhibited in R1 and R2, and meanwhile the decomposition of organic acids was inhibited in R1 and R2. Between days 10 and 16, the pH values of the samples from the different treatments stabilized at about 8 without significant differences between treatments. The high pH may be due to the mineralization of organic nitrogen to ammonia nitrogen [15].

The variations in the EC in all of the treatments are shown in Fig. 10b, and it can be seen that the EC showed an increasing trend in all of the experiments. This could have been caused by the concentrating effect of the loss of water and the release of mineral salts and ammonium ions caused by the decomposition of organic matter [16–18]. After day 10, the EC was lower in R1 than in the other treatments, which might have been caused by the moisture content being higher in R1 than in the other treatments, leading to the very poor decomposition of organic matter in R1.

Effects of PAM on the Biodegradation Process

The alkali extractable organic-C is produced and the humic acid-like organic-C increases during composting, so the percentage of humic acids can be used as an index of compost humification [19]. As Table 3 shows, the significant differences in the percentage of humic acid values in each of the treatments could be seen on day 16, and R2 was found to be the most mature, and R3 was also more mature than R4. This indicates that 0.1% PAM had a positive effect on the maturity achieved in the composting system, and this was because the PAM delayed the decrease in the percentage of CW and moisture content. This effect was not apparent in R1, and this was due to the water not being completely dispersed in the materials when PAM was added. This indicates that the time that PAM is added is a key parameter and that this time should be determined by the changes in the water states in the composting system, in that the water should be completely dispersed and the water states should show a relatively stable trend and that the percentage of CW shows a downward trend.

The biochemical composition of the kitchen waste was determined by a crude fiber analysis and expressed as the percentage of total solids at each sampling point. The biochemical fractions of the biowaste were divided into two fractions, the NDS and NDF. The NDF can be further subdivided into three major fractions: hemicellulose, cellulose, and lignin [20]. As Fig. 11 shows, the NDS was the predominant organic matter component in the composting systems containing kitchen waste, and

Table 3 Percentage of humic acids of the initial and final compost (%)

	R1	R2	R3	R4
Initial	9.63 ± 2.24			
Final	20.47 ± 1.86	25.53 ± 1.81	22.82 ± 0.69	21.36 ± 0.39

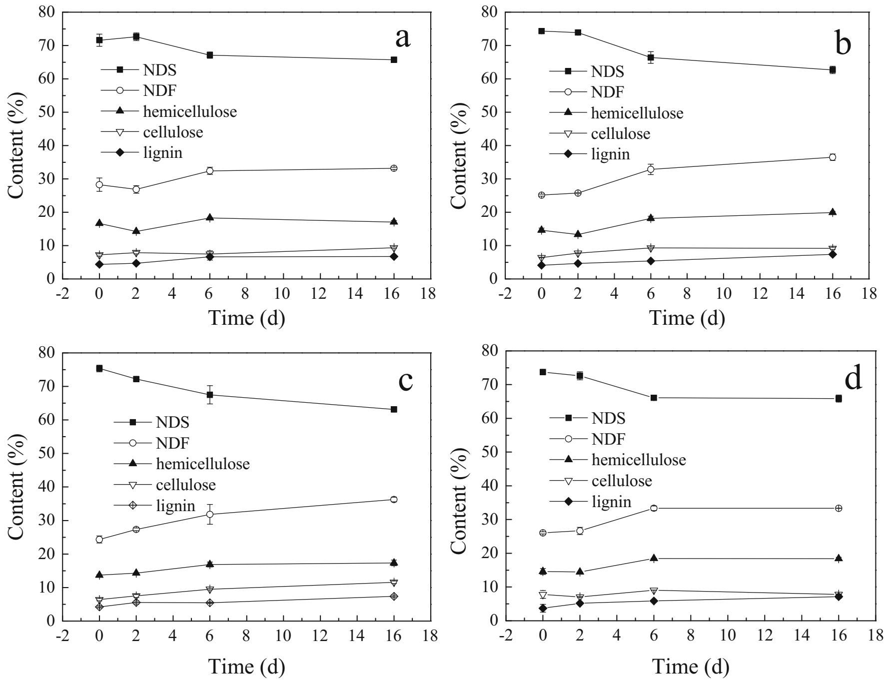

Fig. 11 Biochemical fractions (NDS, NDF, hemicellulose, cellulose, and lignin) in the KW composting process (**a**, **b**, **c**, **d** represented R1, R2, R3 and R4, respectively)

the main NDF component was hemicellulose. In all of the experiments, NDS decreased strongly within the first 6 days of composting, during which time the mineralization of easily biodegradable organic matter by the microorganisms dominated the decomposition of organic matter [21].

The better percentage of humic acid performances in R2 and R3 indicated that more lignin had been transformed into humic acids in these experiments, and although an increase in the lignin content was observed in R2 and R3, a decrease in NDS was also observed in R2 and R3. This suggests that the actual NDS degradation rates were higher in R2 and R3 than in R1 and R4.

The variations that were seen in every biochemical fraction suggest that adding PAM after the water had been completely dispersed in the material promoted the degradation of NDS, as well as the humification of the organic matter.

Summary

PAM can significantly enhance the capillary force and delay the decrease in moisture content and CW during aerobic decomposition, and improve the composting process. However, the effects of PAM on the humification degree of the product and the degradation of biochemical fractions are also affected by the time that the PAM is added. To maximize its performance, add PAM to the composting of kitchen waste when the water has been completely dispersed and the moisture content has not decreased significantly. The initial stage of the thermophilic phase is the optimal time to add PAM to the composting of KW.

2.3 Kitchen Waste Co-digestion with Fruit and Vegetable Waste

FVW is another kind of organic solid waste that mainly comes from food markets and households. FVW comprise 25–30% of the total yield of fruits and vegetables. Reports have indicated that almost 100 million tons of FVW are discarded every year in China [22]. Compared with KW, FVW has low salinity and fat content. Therefore, we suggest that the co-digestion of FVW and KW by AD may be a good choice to treat them. Co-digestion may also promote the co-disposal of two kinds of special organic solid waste. This case aims to develop a solid waste co-disposal method that is economically and technically feasible.

2.3.1 Materials and Methods

The KW and FVW were cut into pieces with a particle size lower than 5 mm using a multifunctional food mixer (Philip I-IR-2860, Netherlands). The inoculated sludge of the two-phase AD was a type of salinity-tolerant anaerobic sludge with the highest tolerable salinity concentration of 3% after 126 days of acclimatization [22]. The characteristics of KW, FVW, and inoculated sludge are shown in Table 4.

The two-phase AD consists of APR and MPR. The APR was made out of a 2.5 L glass bottle. The MPR was an upflow anaerobic sludge bed with a diameter, height, and active volume of 56 mm, 500 mm, and 1.2 L, respectively. The specific pieces of equipment are shown in Fig. 12.

Sixteen APRs and four MPRs were set. Each MPR matched four APRs that had similar proportions of KW and FVW. All of the reactors run in a greenhouse (30–33°C). Detailed information on the material composition within the mixtures in the APR can be found in Table 5. Every APR was inoculated with KW, FVW, and acclimated sludge. The total matrix volume was about 1.5 L, and the sludge concentration was 20 g L^{-1}. According to the pre-experimental results, the COD of all APR had a significant drop on day 9. To improve the sludge adaptability, all of

Table 4 Characteristics of experiment materials (wet weight)

	TS (%)	Salinity (%)	Fat content (%)	pH
KW	10.12 ± 0.27	0.20 ± 0.02	0.43 ± 0.08	6.53 ± 0.01
FVW	10.06 ± 0.07	0.65 ± 0.03	0.22 ± 0.04	6.21 ± 0.02
Inoculated sludge	14.81 ± 0.24	2.94 ± 0.13	/	7.39 ± 0.05

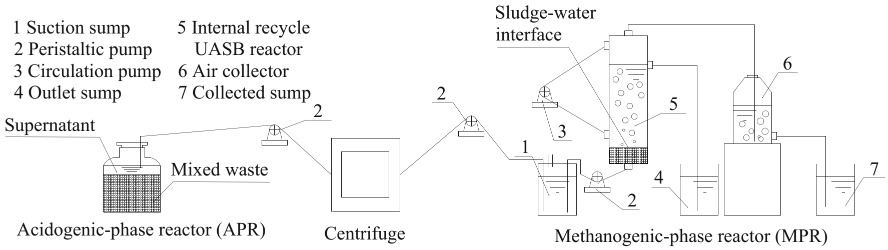

Fig. 12 The reactor of two-phase AD [11]

Table 5 The material composition within the mixtures of the APR

APR	A	B	C	D
Total mass (g)	1,551.60	1,586.25	1,590.90	1,655.55
KW (g)	375.00	750.00	1,125.00	1,500.00
FVW (g)	1,125.00	750.00	375.00	0
Inoculated sludge (g)	30.00	30.00	30.00	30.00
Salinity (g)	11.25	22.50	33.75	45.00
Fat content (g)	22.50	45.00	67.50	90.00

Every set of devices (A, B, C, D) had four APRs, each one of them operated at different HRTs of 5, 10, 15, and 20 days, respectively. The corresponding MPR was named a, b, c, and d, respectively

the APRs were pre-run for 10 days without continuous feedstock, sampling and determination, as in the following trials. To optimize the HRTs of A, B, C, and D, all of the APRs were first run for 24 days with the set HRT, and the pH, VS, TS, VFA, and COD of all the supernatants were determined. After optimization, all of the APRs were set to run with their corresponding optimal HRT. When the operation of all the APRs was stable, all of the MPRs were started.

In each MPR, the initial sludge concentration was set as 50 g L^{-1}. During the running process, the supernatant from each group of four APRs was centrifuged daily and merged as the influent of the MPR. Considering the low pH shock, the pH of the influent was first adjusted to 5.5–6.0. The influent was then pumped into the MPR through a peristaltic pump. The influent water flow rate was initially set as 12–13 mL h^{-1}. Subsequently, the water flow rate was improved to shorten the HRT and to enhance the load of MPR step by step according to its running status. To keep raising the flow rate and buffer the high COD concentration in the MPR, the internal reflux was continuously carried using a peristaltic pump with a flow rate of 2–2.5 mL min^{-1}.

2.3.2 Results

Effect of HRT on APR

The pH of the APRs with different KW proportions varied greatly as the HRT. Figure 13 shows the pH of the APR with 25% KW after stabilization for 18 days, whereas the others only required 12 days. The main reason for the difference was that the FVW proportion of APR with 25% KW (75% FVW) was significantly higher than that of the others (50%, 25%, and 0% FVW, respectively) ($p < 0.05$). The KW included 70% rice in the total wet weight, and the rice is full of carbohydrate, and the carbohydrate is more easily degradable than hemicellulose, cellulose, and lignin. So, the hydrolysis efficiency of KW was higher than that of FVW. And the pH of all APRs was lower than 4.0, and the reason for this performance was that high organic content could improve the degree of acidification.

Specifically, in APR A (25% KW), the change in pH of each APR had a wider range, and the final pH of APR A_{15} (HRT = 15 days) was higher than the other APRs (pH(A_{15}) = 3.88, pH(A_5,A_{10},A_{20}) = 3.21 ± 0.05); the high pH means low VFA accumulation [23], so this result suggested that 15 days is not an appropriate HRT for APR A. At the preliminary stage (0–6 days), the change in pH of APR A may have been caused by the 25% KW having a low salinity and fat content, and the microbes hadn't been inhibited by this salinity and fat content. The pH of all APR A

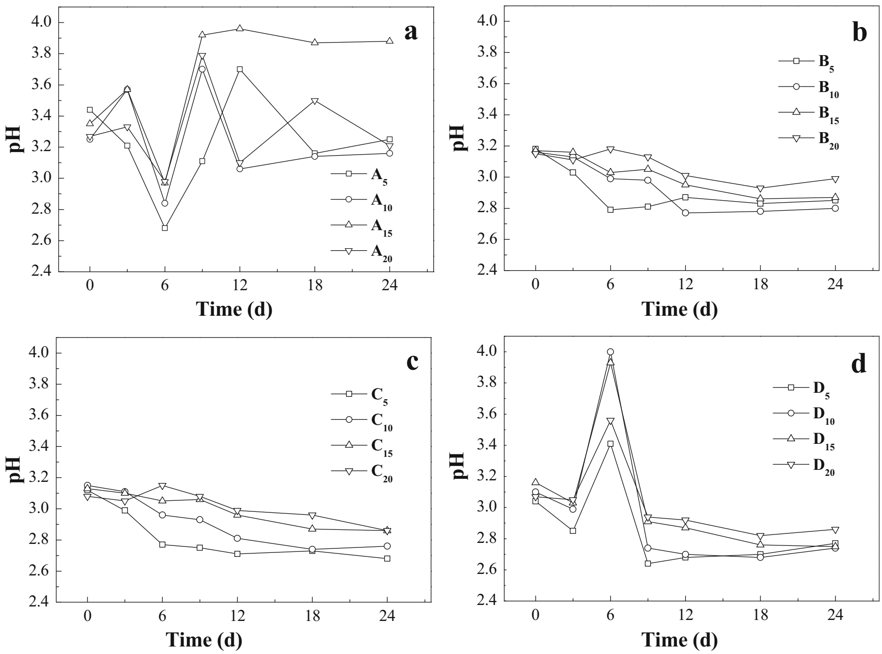

Fig. 13 The change in pH of each APR at different HRT

was below 3.0 on day 6, meaning that the degree of acidification was great. In APR B and APR C, the changes in pH had a lesser range. All of the APRs of the B and C series (with an HRT of 5, 10, 15, and 20 days, respectively) exhibited a similar trend. This trend suggested that the APR of 50 and 75% KW could offer appropriate conditions with moderate salinity and fat concentration. For APR D, there was a drastic change in the pH at the beginning of the 9th day, and there was a sharp rise followed by a slower decline, which ended up with a sharp decline. At the preliminary stage (day 0–6th), the acidification was inhibited by low microbial activity. Then the microbe adjusted to the above feeding method, the microbial activity was renewed, and the pH declined again. The trend also indicated that the adaptation time of the sludge should be more than 10 days in APR D, and this may be caused by the high salinity and fat content.

In the acidogenic stage of AD, the acidogenic bacteria consumed organic matter, which caused a corresponding change in the TS and VS of the matrix. Therefore, the ratio of VS/TS could indirectly characterize the degradation degree of the material. The changes in VS/TS (%) of the APR at different HRTs were shown in Table 6. In all of the APRs with 25% KW, the degradation rate of the APRs with HRTs of 5 and 10 days were higher than those with HRTs of 15 and 20 days. This result suggested that 5–10 days may be the optimal HRT of APR with 25% KW. In all of the APR B with 50% KW, if the HRTs were 5, 15, and 20 days, the degradation rate would be higher than the HRT of 10 days. In all of APR C and D, the degradation rates of APR C_{15} and D_{20} were higher than those of the others. Thus, APR C_{15} and D_{20} can be used as optimal APRs.

Table 6 The daily discharge and feedstock of each APR at different HRT

APR	HRT (days)	Discharge (g)	Feedstock			
			KW (g)	FVW (g)	Salinity (g)	Fat content (g)
A	5	300.00	75.00	225.00	2.25	4.50
	10	150.00	37.50	112.50	1.13	2.25
	15	100.00	25.00	75.00	0.75	1.50
	20	75.00	18.75	56.25	0.56	1.13
B	5	300.00	150.00	150.00	4.50	9.00
	10	150.00	75.00	75.00	2.25	4.50
	15	100.00	50.00	50.00	1.50	3.00
	20	75.00	37.50	37.50	1.13	2.25
C	5	300.00	225.00	75.00	6.75	13.50
	10	150.00	112.50	37.50	3.38	6.75
	15	100.00	75.00	25.00	2.25	4.50
	20	75.00	56.25	18.75	1.69	3.38
D	5	300.00	300.00	0.00	9.00	18.00
	10	150.00	150.00	0.00	4.50	9.00
	15	100.00	100.00	0.00	3.00	6.00
	20	75.00	75.00	0.00	2.25	4.50

Table 7 The change in VS/TS (%) of each APR at different HRT

Time (days)	0	3	6	9	12	18	24
A_5	37.70	33.33	32.65	28.57	26.66	25.60	25.59
A_{10}	36.36	33.85	34.62	28.07	24.49	24.19	23.63
A_{15}	37.29	34.29	35.35	32.31	31.58	29.24	29.19
A_{20}	39.66	38.81	36.84	33.33	32.73	30.30	28.87
B_5	36.75	33.96	34.04	34.21	38.24	30.72	28.26
B_{10}	34.71	35.48	32.79	31.58	33.33	29.71	28.16
B_{15}	37.88	35.29	33.67	31.82	32.79	31.34	30.40
B_{20}	38.81	38.24	33.33	33.80	33.33	31.46	31.31
C_5	37.14	41.79	34.04	36.00	36.23	36.73	33.05
C_{10}	38.14	37.04	33.33	32.69	35.51	34.55	34.22
C_{15}	38.71	37.18	37.29	35.09	35.00	33.90	34.00
C_{20}	40.00	37.66	36.25	36.17	35.16	37.50	37.49
D_5	34.95	39.22	32.36	38.18	29.69	24.72	29.51
D_{10}	37.22	41.82	34.79	37.50	34.52	31.00	31.06
D_{15}	41.10	40.74	38.96	38.98	37.21	36.17	35.30
D_{20}	40.00	40.83	38.55	39.66	35.71	33.56	33.17

In the acidogenic stage of AD, the ratio of VFA/CODs can indirectly characterize the acidification degree of the materials. The changes in VFA/CODs of APR at different HRTs are shown in Table 7. There was a decreasing trend in the VFA/CODs with the increase in the proportion of KW. These results can be attributed to the increase in concentrations of salinity and fat in the matrix. The high concentrations of salinity and fat can seriously inhibit the microbial activity, while the acidification degree decreased correspondingly.

The results further indicated that the APRs with KW of 25%, 50%, 75%, and 100% had the highest acidification degree at 85.66%, 74.11%, 70.11%, and 56.63% when their HRTs were 10, 15, 15, and 20 days, respectively.

Performance of MPR

The changes in pH and alkalinity of the MPR effluent are shown in Fig. 14. These data indicated that the process consisted of two periods before the HRT of MPR was changed. The first was the adjustment phase (day 0–8), and the second was the stationary phase (days 10–15). The effluent pH and alkalinity rose with the fluctuations in the first 8 days and then became relatively steady from day 10 to 15. After day 15, the MPR HRT was adjusted from 4 to 3 days. The change in pH and alkalinity showed a similar trend in that all of the MPRs had a sudden decrease on day 16. In all of the MPRs, the pH and alkalinity gradually increased and then stabilized within a specific range in the former 15 days (HRT = 4 days).

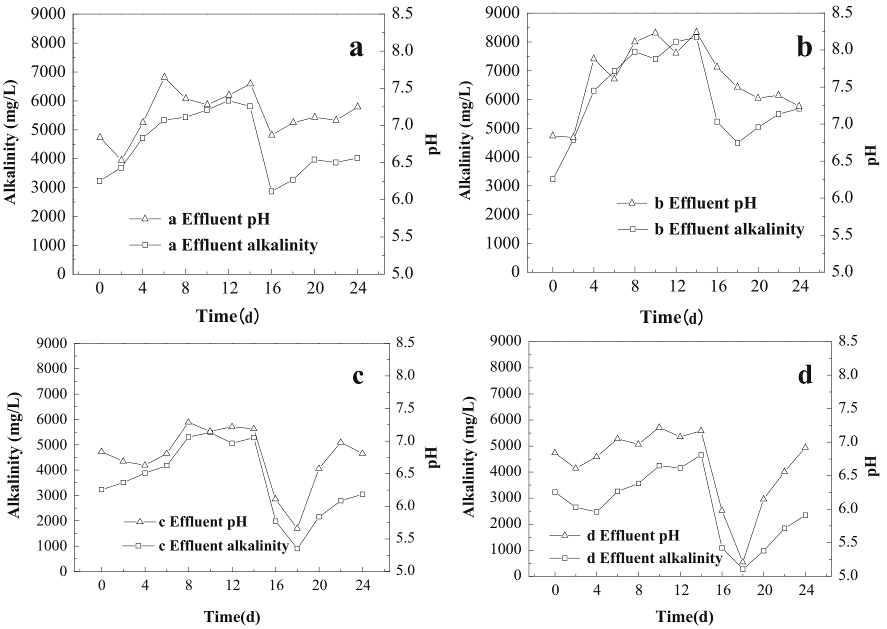

Fig. 14 The change in pH value and alkalinity in each MPR

In MPRs a and b, the pH and alkalinity decreased after the increase in the organic load, but recovered rapidly with the extension of the fermentation time. After day 20, the pH and alkalinity stayed at a relatively stable level, indicating that the optimal HRT of MPRs a and b was 3 days, but the final alkalinity was slightly lower than that of 4 days. The results showed that alkalinity gradually and consistently increased with the extension of HRT.

In MPRs c and d, pH and alkalinity decreased after the enhancement of the organic load, but did not recover as in MPRs a and b. The main reason could be the higher concentrations of salinity and fat of the influent of MPRs c and d. Therefore, the impact of adjusting HRT was greater in MPRs c and d. To avoid further acidification, the HRT was adjusted back to 4 days on day 18. Subsequently, the pH and alkalinity returned to their former levels, indicating that the optimal HRT of MPRs c and d was 4 days. Thus, the MPR with a higher KW proportion should run in a short HRT.

The changes in daily methane production are shown in Fig. 15. The figure revealed that all of the trends were similar to the changes in pH and alkalinity and that the optimal tested HRTs of MPRs a, b, c, and d were 3, 3, 4, and 4 days, respectively. Moreover, the daily methane production of MPR b was higher than that of the others after becoming stable. This difference could be because MPR b could provide more sufficient nutrients for methanogens than MPR a. At the same time, MPR b reduced the negative impact caused by high concentrations of salinity and fat compared with MPRs c and d.

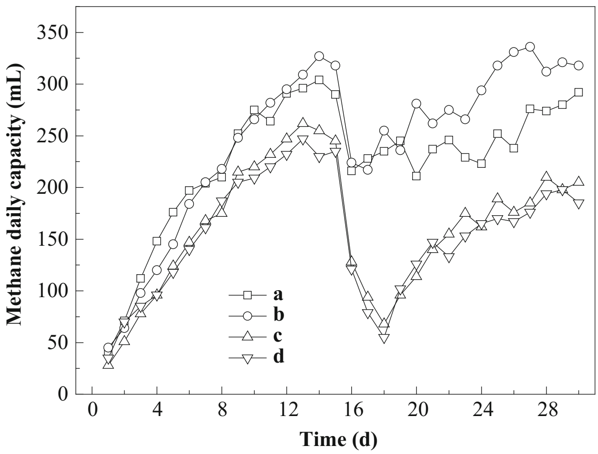

Fig. 15 The change in daily methane production in each MPR

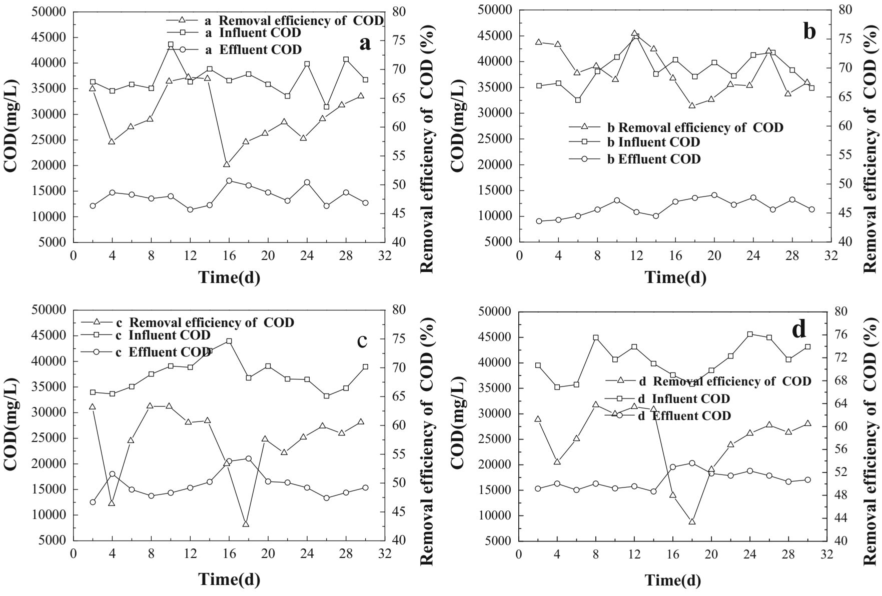

Fig. 16 The change in COD in each MPR

Figure 16 shows that the influent COD was high and changeable. In day 2, all of the MPRs had a higher COD removal efficiency. In comparison, in MPRs a, c, and d on day 4 (MPR b on day 6), the COD removal efficiency followed a sharp downward trend, and then showed an upward trend from days 5 to 10 (MPR b on days 7–12), finally remained relatively stable from days 10 to 14 (MPR b had a slight downward trend on day 14). This result could be due to the adsorption of sludge, which caused the COD removal efficiency to remain at a high level in the beginning. Thus, when the COD removal efficiency decreased later, it could have been caused by the desorption of sludge and microorganisms that cannot adapt fully to the environment. As the reaction proceeded, the adaptability of the methane bacteria was enhanced and then the methane production increased, which also resulted in the gradual rise in the COD removal efficiency.

After running for 15 days, the HRTs were changed from 4 to 3 days in all of the reactors. The trends of COD removal efficiency were similar to the changes in pH value, alkalinity, and methane production. After the HRT was shortened, the COD removal efficiency of MPR b did not exhibit a significant downward trend compared with MPRs a, c, and d ($p > 0.05$). The COD removal efficiency of MPRs c and d was lower than that of MPRs a and b in the stationary phase, and the COD removal efficiency of MPRs c and d decreased rapidly. These findings indicated that the methanogenus did not resume activity as MPRs a or b. Thus, the HRT of MPRs c and d was restored to the original 4 days, which caused the COD of the effluent to slowly decline and the removal rate to gradually increase. The higher load of salinity and fat concentration had a negative effect on the microbial activity because the KW proportion was higher in MPRs c and d than in the others.

The results of the COD removal efficiency showed that the optimal HRT of MPRs a and b was 3 days, whereas that of MPRs c and d was 4 days. The COD removal efficiency of MPR b was higher than that of the others. Thus, MPR b exhibited a better performance with the change of HRT.

As shown in Fig. 17, the VFA of the influent was high and changeable, with a range of 8,000–12,000 mg L^{-1}. The VFA performance indicated a similar trend as the abovementioned parameters.

In MPRs a and b, the VFA removal efficiency reached more than 90% in the stationary phase (days 10–15). However, after the HRT was changed from 4 to 3 days, the concentration of the effluent VFA rose and the VFA removal rate dropped to below 80% (days 15–20) in MPR a. In comparison, in MPR b, the change in the effluent VFA was not significant ($p > 0.05$), and the removal efficiency remained above 85%.

In MPRs c and d, after the HRT was changed from 4 to 3 days, the VFA removal efficiency rapidly dropped and did not return to its original rate (days 15–18). Thus, the HRT was changed to the original 4 days and the VFA removal efficiency returned to 85%.

The results showed that the optimal HRT of MPRs a and b was 3 days, and the optimal HRT of MPRs c and d was 4 days. The VFA removal efficiency of MPRs a and b was higher than that of the others, and MPR b had a better performance with the change of HRT.

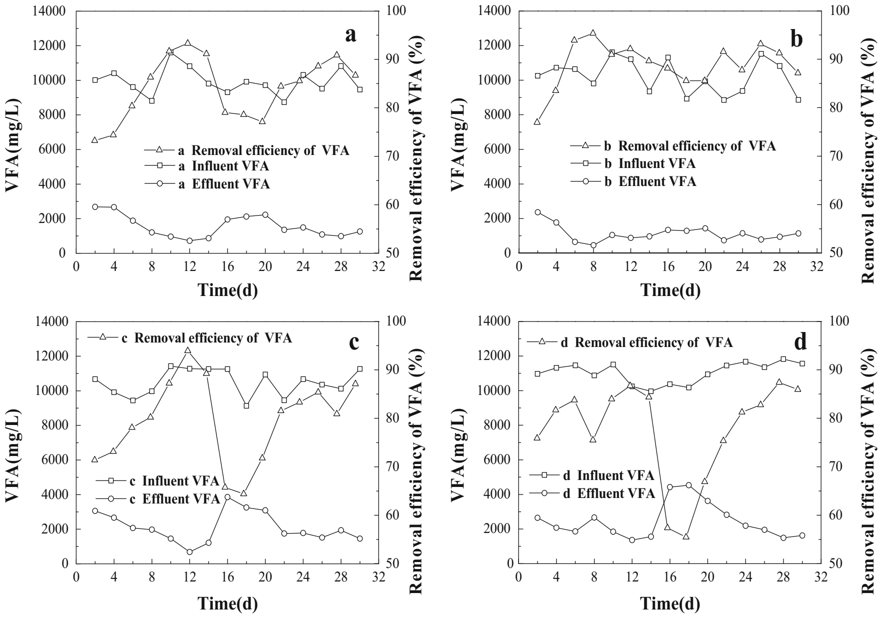

Fig. 17 The change in VFA in each MPR

2.3.3 Summary

The addition of FVW can reduce the HRT and lead to a higher degree of acidification. 25% FVW was better than the others in APR. In MPR, the optimal HRTs of 25 and 50% were 3 days, and the optimal HRTs of 75 and 100% were 4 days. The two-phase AD system with 50% KW not only can dispose more KW than the two-phase AD system with 25% KW but also have better stability in MPR. The 50% KW is the best ratio in this two-phase AD system.

3 Conclusion

MSW digestion without separation is a possible means of refuse disposal. The refuse and leachate in the reactor connected with the aged refuse column reached a strongly degraded and more stable state compared with directly recycled leachate. The key constituents in the leachate, such as COD, NH_4^+-N, and TN, could meet the related discharge criteria. However, the stabilized refuse needs further disposal.

KW composting after source separation is a better choice. However, the high water content is the key issue that needs attention. The percentage of CW decreases while the percentage of EW increases as the composting progresses. The percentage of EW correlated linearly well with dissolved organic carbon, EC, pH, and C/N ratio and is affected by hemicellulose and cellulose. PAM can significantly enhance the capillary force and delay the decrease in moisture content and CW during aerobic decomposition and improve the composting process.

KW co-digestion with FVW has high application potential. The addition of FVW can reduce the HRT and lead to a higher degree of acidification. Twenty five percent FVW was better than the others in APR. In MPR, the optimal HRT of 25 and 50% was 3 days, and the optimal HRT of 75 and 100% was 4 days. The two-phase AD system with 50% KW not only can dispose of more KW than the two-phase AD system with 25% KW but also have the better stability in MPR. Therefore, the results suggested that the 50% KW is the best ratio in this two-phase AD system.

References

1. World Bank (2012) What a waste: a global review of solid waste management. Urban Development and Local Government Unit, The World Bank, Washington, DC
2. Huo SL, Xi BD, Yu HC, Fan SL, Su J, Liu HL (2008) In situ simultaneous organics and nitrogen removal from recycled landfill leachate using an anaerobic-aerobic process. Bioresour Technol 99:6456–6463
3. Borglin SE, Hazen TC, Oldenburg CM, Zawislanski PT (2004) Comparison of aerobic and anaerobic biotreatment of municipal solid waste. J Air Waste Manage Assoc 54:815–822
4. Nguyen PHL, Kuruparan P, Visvanathan C (2007) Anaerobic digestion of municipal solid waste as a treatment prior to landfill. Bioresour Technol 98:380–387
5. Long Y, Guo QW, Fang CR, Zhu YM, Shen DS (2008) In situ nitrogen removal in phase-separate bioreactor landfill. Bioresour Technol 99:5352–5361
6. He R, Shen DS, Wang JQ, He YH, Zhu YM (2005) Biological degradation of MSW in a methanogenic reactor using treated leachate recirculation. Process Biochem 40:3660–3666
7. Wang Q, Matsufuji Y, Dong L, Huang QF, Hirano F, Tanaka A (2006) Research on leachate recirculation from different types of landfills. Waste Manag 26:815–824
8. Bilgili MS, Demir A, Ozkaya B (2007) Influence of leachate recirculation on aerobic and anaerobic decomposition of solid wastes. J Hazard Mater 143:177–183
9. Vigneron V, Ponthieu M, Barina G, Audic JM, Duquennoi C, Mazeas L, Bernet N, Bouchez T (2007) Nitrate and nitrite injection during municipal solid waste anaerobic biodegradation. Waste Manag 27:778–791
10. Nikolaou A, Giannis A, Gidarakos E (2010) Comparative studies of aerobic and anaerobic treatment of MSW organic fraction in landfill bioreactors. Environ Technol 31:1381–1389
11. Yang YQ, Shen DS, Li N, Xu D, Long YY, Lu XY (2013) Co-digestion of kitchen waste and fruit–vegetable waste by two-phase anaerobic digestion. Environ Sci Pollut Res 20:2162–2171
12. Miller JH (1992) A short course in bacterial genetics: a laboratory manual and handbook for E. coli and related bacteria. Cold Spring Harbor Laboratory Press, Cold Spring Harbor, pp. 24.5–24.6
13. Shen DS, Yang YQ, Huang HL, Hu LF, Long YY (2015) Water state changes during the composting of kitchen waste. Waste Manag 38:381–387
14. Ben-Hur M (1994) Runoff, erosion, and polymer application in moving-sprinkler irrigation. Soil Sci 158:283–290
15. Venglovsky J, Sasakova N, Vargova M, Pacajova Z, Placha I, Petrovsky M, Harichova D (2005) Evolution of temperature and chemical parameters during composting of the pig slurry solid fraction amended with natural zeolite. Bioresour Technol 96:181–189

16. Maeda KK, Hanajima D, Morioka RK, Osada TKS (2010) Characterization and spatial distribution of bacterial communities within passively aerated cattle manure composting piles. Bioresour Technol 101:9631–9637
17. Nair J, Okamitsu K (2010) Microbial inoculants for small scale composting of putrescible kitchen wastes. Waste Manag 30:977–982
18. Said-Pullicino D, Erriquens FG, Gigliotti G (2007) Changes in the chemical characteristics of water-extractable organic matter during composting and their influence on compost stability and maturity. Bioresour Technol 98:1822–1831
19. Iglesias-Jiménez E, Pérez-García V (1992) Composting of domestic refuse and sewage sludge. II. Evolution of carbon and some “humification” indexes. Resour Conserv Recycl 6:243–257
20. Francou C, Linères M, Derenne S, Villio-Poitrenaud ML, Houot S (2008) Influence of green waste, biowaste and paper–cardboard initial ratios on organic matter transformations during composting. Bioresour Technol 99:8926–8934
21. Pichler M, Kögel-Knaber I (2000) Chemolytic analysis of organic matter during aerobic and anaerobic treatment of municipal solid waste. J Environ Qual 29:1337–1344
22. Xu D (2011) Investigation of food wastes and optimization in anaerobic fermentation process. Dissertation of master’s degree, Zhejiang Gongshang University, Zhejiang (in Chinese)
23. Han SK, Shin HS (2004) Biohydrogen production by anaerobic fermentation of food waste. Int J Hydrog Energy 29:569–577

E-Waste Collection and Treatment Options: A Comparison of Approaches in Europe, China and Vietnam

Stefan Salhofer

Abstract E-waste is a complex waste stream with several categories of products, each of them requiring a specific treatment technology. This chapter analyses the status quo of e-waste management in three global regions, where the European Union represents a frontrunner in environmental legislation and implementation; China, catching up with recent legislation and large-scale investments in recycling infrastructure; and Vietnam, as an example for the numerous countries where an unregulated situation dominates. This chapter aims at giving an overview of the management of this waste stream focussing on two relevant stages in the material recovery chain: collection as the interface between consumers and waste management and treatment with an overview of technologies applied for the removal of hazardous materials and the recovery of valuable materials such as steel, copper, plastics and others. Challenges for these situations are identified.

Keywords Collection, E-waste, Recycling, Source separation, Treatment

Contents

S. Salhofer (✉)
University of Natural Resources and Life Sciences, Vienna, Wien, Austria
e-mail: stefan.salhofer@boku.ac.at

R. Maletz et al. (eds.), *Source Separation and Recycling*,
Hdb Env Chem (2018) 63: 227–244, DOI 10.1007/698_2017_36,
© Springer International Publishing AG 2017, Published online: 28 April 2017

1 Introduction

End-of-life electrical and electronic equipment (here referred to as e-waste) is more complex than other waste streams in terms of material composition and the content of hazardous materials. On the input side of recycling processes, this waste stream consists of a number of product categories (e.g. ten categories in the WEEE I Directive 2002/96/EC) [1], which have rather different properties and need to be treated separately. Specifically, cooling and freezing equipment (containing CFCs in the coolant circuit and the insulation) requires a specific technology, and the same holds true for fluorescent lamps and screens.

In a global perspective, different levels of regulation have been established, stretching from unregulated situations in most of the low-income countries to comprehensive legislation, including the role of producers in Extended Producer Responsibility (EPR) schemes, mainly found in EU member states and some other countries. More details on EPR can be found at OECD [2].

This chapter aims at giving an overview of the management of this waste stream focussing on two relevant stages in the material recovery chain: collection as the interface between consumers and waste management and treatment with an overview of technologies applied for the removal of hazardous materials and the recovery of valuable materials such as steel, copper, plastics and others. To demonstrate differences and the wide range of e-waste management implementations, the situation in three global regions with different levels of development is analysed: the European Union as a frontrunner in environmental legislation and implementation; China, catching up with recent legislation and large-scale investments into recycling infrastructure; and Vietnam, as an example for the numerous countries where an unregulated situation dominates. Challenges arising from each of these situations have been identified.

2 Material Properties

E-waste, defined as 'any appliance using electrical power supply that has reached its end of life' [3], comprises a wide range of appliances, which vary considerably in material composition and require different technologies for treatment. Table 1 gives an overview of the composition of e-waste by category. In this text, five categories are used:

- Large appliances (LA) such as washing machines or dishwashers with a high proportion of metals

Table 1 Material composition of e-waste by category (data for LA, C&F, FT and CRT from [4]; data for LCD monitors and LCD TV from [5])

			Screens			
	LA (%)	C&F (%)	CRT (%)	LCD monitor (%)	LCD TV (%)	FT (%)
Hazardous components	0.1	0.5	0.2	0.3	1.1	1.7
Iron and steel	55.9	66.3	5.3	40.9	53.5	1.9
Aluminium	1.7	3.3	1.6	5.2	0.6	5.6
Copper	2.2	2.3				1.8
Cables	1.8	0.3	1.8	1.1	0.9	
Plastics	12.7	25.3	12.7	12.7	25.3	1.7
Printed circuit boards	0.1		9.5	8.1	6.1	0.9
Compounds			6.4			
Other materials	25.5	1.9	62.2	8.1	7.7	86.4
Total	100	100	100	100	100	100

LA large appliances, *C&F* cooling and freezing equipment, *CRT* cathode ray tube devices (TVs and monitors), *LCD monitors* liquid crystal monitors, *LCD TV* liquid crystal television sets, *FT* fluorescent tubes

- Cooling and freezing equipment (C&F) with refrigerators, freezers and air condition equipment where CFC-containing cooling agents and CFCs in the insulation pose specific challenges during the treatment
- Screens with CRT monitors or TV sets with more than 50% glass (here listed as other materials) and LCD screens with higher proportions of plastics and backlights partly containing Hg
- Fluorescent tubes (FT), where the majority of material is glass and the Hg content requires specific treatment
- Small appliances (SA) with several subcategories

In Table 2, more details on small appliances (SA) are given. In this context, SA are defined as all types of e-waste smaller than 50 cm along their longest edge, excluding cooling and freezing equipment, lamps and screens. SA are regarded as the most valuable part of the e-waste stream, containing IT as well as consumer electronics with a higher content of non-ferrous and precious metals. Printed circuit boards contain high concentrations of copper and higher concentrations of precious metals than any other category, which are mainly found in information and communication technology equipment (ICT), e.g. computers, mobile phones, printers, etc., and consumer electronics, such as audio equipment, SAT receivers, etc.

Hazardous components in Tables 1 and 2 summarise all components containing hazardous substances which are listed in Annex VII of the WEEE II Directive 2012/19/EU [7]. The list of hazardous components includes batteries, capacitors (all capacitors containing polychlorinated biphenyls and electrolyte capacitors larger than 25 mm), printed circuit boards (of mobile phones generally or those larger than

Table 2 Material composition of small appliances (SA) by subcategories [6]

	SA (%)	1C (%)	2 (%)	3A (%)	4A (%)	5–9 (%)
Hazardous components	0.9	0.6	0.4	1.3	0.9	0.9
Iron and steel	37.6	71.1	15.9	49.6	37.2	32.5
Aluminium	1.7	0.8	2.0	1.9	2.1	
Copper	1.0	4.1	0.0	0.9	2.8	
Cables	4.1	0.9	6.5	2.8	1.3	8.5
Plastics	29.8	12.7	45.7	31.3	21.3	10.3
Printed circuit boards	5.4	0.2	0.1	9.6	10.1	0.4
Compounds	11.5	5.9	26.3	2.0	6.0	19.1
Other materials	7.9	3.7	3.1	0.5	18.3	28.3
Total	100	100	100	100	100	100

Subcategories: *1C* small household equipment (large), *2* small domestic appliances, *3A* information and communication equipment (without screen), *4A* consumer electronics (without screen), *5–9* other small equipment

10 cm^2), toner cartridges, liquid crystal displays (larger than 100 cm^2 and those back-lighted with gas discharge lamps), mercury-containing components such as switches or backlighting lamps, asbestos-containing components, components containing refractory ceramic fibres, components containing radioactive substances, plastic-containing brominated flame retardants, cathode ray tubes and halogenated coolants.

3 Collection

3.1 E-Waste Collection in Europe

In Europe, most collection schemes for e-waste from households have been set up as part of existing municipal collection schemes for recyclables and hazardous household waste and additional take-back schemes by retailers. In some countries (e.g. Belgium, France), take-back through reuse centres plays an important role, while in others, scrap dealers are a relevant collection avenue (e.g. in Greece).

Quantities of e-waste generated vary considerable between wealthy countries (such as Austria, Belgium, France, Germany and Sweden with more than 20 kg/cap/year) and less affluent ones. Collection quantities range between 4 and 17 kg/cap/year, depending on the development stage of the collection schemes. According to Baldé et al. [8], EU member states on average collected 3.2 from 9 mt generated in 2014, representing an average collection rate of 36%. Most successful collection schemes can be found in Scandinavia (Sweden), where 17.5 kg/cap/year were collected in 2012. More details on the generation and collection rates of e-waste in selected EU member states are shown in Table 3.

Table 3 E-waste quantities generated in 2014 and collected in selected EU member states [8]

	E-waste generated (kg/cap/year)	E-waste collected (kg/cap/year)	Year
Austria	22.0	9.0	2012
Belgium	21.4	10.3	2012
Bulgaria	10.7	5.3	2012
France	22.1	6.8	2010
Germany	21.6	8.5	2012
Greece	15.1	4.2	2010
Italy	17.6	3.8	2012
Sweden	22.2	17.5	2012

In western European member states, the initial collection target from the WEEE I Directive [1] of 4 kg/cap/year is met easily, while for new member states, it is still a challenge. Under the WEEE II Directive [7], higher collection targets, i.e. 65% of the quantity put on the market or alternatively 85% of e-waste in waste streams, are mandatory from 2019 onward. To cope with this, several cities and regions in Europe have started to identify options to raise the collection efficiency. Besides conventional take-back at municipal collection sites, the following collection routes have been tested:

- Kerbside collection at multifamily dwellings as a convenient option for residents of densely populated areas. A collection trial at a multifamily dwelling in Vienna showed collection rates of SA of 0.4–1.1 kg/cap/year, and kerbside collection with containers in Copenhagen reached 1.33 kg/cap/year [9].
- Another approach is to instal container collection in public places. Case studies have been found for Sweden and Germany, where collection rates for SA range from 0.04 to 0.84 kg/cap/year (cf. [10]). However, this unmanned and uncontrolled way of collection is increasingly considered unsafe following a series of fire incidents at e-waste storage and recycling facilities caused by self-igniting lithium ion batteries.
- Intensified collection of SA at retail outlets. Two case studies from Sweden and Germany show low collection rates (cf. [10]).

The challenge in e-waste collection in Europe in the coming years will be to identify ways to intensify collection by offering a better collection service to households and providing more information to motivate citizens for collection. Further, illegal exports from Europe will lead to a loss of resources for the European industry. In Germany, the amount of illegal exports in 2008 was estimated at 155,000 t [11]. These exports were heavily criticised and are now subject to more detailed regulations in Annex VI of the WEEE II Directive [7], which define the circumstances under which exports may take place.

3.2 E-Waste Collection in China

The generation rate of e-waste for China is estimated at 6.0 mt/year (2014), and the collection rate for 2013 is given at 1.3 mt [8]. Today, informal structures dominate e-waste collection and take-back, as they have wide urban collection networks, offer high reimbursements to consumers and have access to a bigger and cheaper labour force compared to formal collection channels. These characteristics have already been identified in the first pilot trials with formal collection schemes in which attaining sufficiently high rates in e-waste collection posed the major problem, as collection systems were either controlled or strongly permeated by informal actors [12–15]. The Chinese government has been learning from these initial difficulties: the 'Old for New' scheme (OfN) tried to make the formal collection system more attractive in two ways. On the one hand, electronics retailers and other formal take-back entities were given subsidies to offer incentives to consumers to return their e-waste to formal channels. On the other hand, recyclers also received comparatively high subsidies, enabling them to successfully compete with informal collection systems [16–18].

The results in terms of collection rates in the OfN programme are shown in Table 4. Although the OfN scheme has achieved respectable collection rates (0.4–2.1 kg/cap/year), the persistent problem for the formal system remained the collection costs, which primarily originate as a consequence of competition with the informal sector. Compared to private enterprises in the government pilots, the informal sector has lower personnel costs related to collection and recycling, which allows it to pay higher prices for e-waste originating from households and companies [20].

Table 4 Collection rates in the 'old for new' pilot scheme [19]

Region	Inhabitants (1,000)	TV sets (kg/cap/year)	Refrigerators (kg/cap/year)	Washing machines (kg/cap/year)	Air conditioners (kg/cap/year)	Computers (kg/cap/year)	Total (kg/cap/year)
Beijing	19,600	0.64	0.16	0.73	0.05	0.04	1.62
Tianjin	12,280	0.50	0.08	0.42	0.02	0.02	1.04
Shanghai	23,019	1.62	0.07	0.33	0.02	0.03	2.08
Jiangsu province	77,250	0.67	0.04	0.27	0.01	0.01	1.00
Zhejiang province	51,800	0.54	0.03	0.12	0.01	0.03	0.74
Fuzhou	3,380	0.74	0.03	0.21	0.01	0.01	0.99
Shandong province	95,790	0.30	0.03	0.13	0.00	0.01	0.47
Changsha	7,044	0.55	0.05	0.25	0.02	0.00	0.86
Guangdong	104,300	0.19	0.03	0.18	0.03	0.00	0.44

In fact, the informal segment still dominates the collection of e-waste from households. The entangled relationship between urban residents and informal collectors has been stated in previous research as a major reason for this development (compare [12, 17, 20, 21]) and may in essence originate in the societal value structure of urban Chinese society: Household waste, including e-waste, is widely perceived as a valuable commodity and thus is expected to be exchanged for money. Unsurprisingly, residents thus prefer informal collection systems for e-waste, e.g. 71% in Beijing [21], since they offer pecuniary reimbursements and convenient doorstep collection services. In fact, many major Chinese cities exhibit high amounts of informally collected e-waste from households (see Table 4) that by far exceed formally collected or received amounts.

The challenge in e-waste collection in China is the fact that informal collection is by far the most convenient option for residents: collectors pick up e-waste (and other recyclables) at the household and even pay some money to receive it. As residents do not need to take any action, they prefer this collection path to others which will require them to bring e-waste to collection points. Informal collectors work under unregulated labour conditions, often lacking social security and social acceptance. This needs to be seen in the wider context of informal work where waste collection and recycling represent only a smaller sector. For more details on informal work in China, see Baum [22].

3.3 E-Waste Collection in Vietnam

Vietnam, a country with about 93m inhabitants, has a generation rate estimated at 2.6 kg/cap/year, leading to a national waste generation rate of 0.23 mt/year; however, the data for collection rates are not available [23]. As no formal collection scheme for e-waste exists, collection takes place through informal collectors. There are thousands of peddlers who collect disposed appliances from end users and sell them to service shops or traders. They are seen as 'saviours' for e-waste, achieving high collections rates [23]. The peddlers use motorcycles, bicycles or even bamboo frames on their shoulders, moving from house to house to buy e-waste (and other recyclable waste) and bring it to the places where those items can be sold at a higher price. This informal e-waste handling system is very active and successful [24].

Challenges for e-waste collection in Vietnam are both the lack of a formal collection scheme and the labour conditions of informal collectors.

4 Treatment

4.1 Treatment in Europe

The treatment process for e-waste typically includes dismantling, processing and end processing. Dismantling is the first step to separate hazardous components as well as valuable components. In the subsequent processing, materials are fragmentised to liberate the materials from compounds and separated. End processing means those processes where the materials end up, e.g. steel scrap ending up in steel mills to be re-melted, plastic being re-granulated after sorting and cleaning or the disposal of hazardous components at hazardous waste treatment facilities. The processes applied vary considerably by product category:

For large appliances, e.g. washing machines, dishwashers, etc., the treatment starts with the removal of hazardous components by dismantling (capacitor, Hg components), followed by mechanical processing using shredder and separation technologies (magnetic separation, eddy current separator, etc.).

Cooling and freezing equipment, e.g. refrigerators and freezers, is processed at dedicated installations to remove CFCs from the cooling circle; in a next step, CFCs are removed from insulation using encapsulated cutting mills with pressure, followed by mechanical processing. It is important to note that CFCs are increasingly being replaced by other cooling agents; thus a future challenge for the recycling industry will be the identification of equipment that contains CFCs.

Lighting equipment, i.e. fluorescent lamps and compact fluorescent lamps, are treated by crushing or cutting, and this needs to take place in encapsulated machinery to avoid the emission of Hg vapour. The output materials represent low value.

For screens, different technologies are used: CRT monitors and CRT TV sets go to dismantling and specific treatment to separate the glass. For flat screens, there are new technologies for LCD treatment, as these partly contain fluorescent tubes containing Hg.

Small appliances undergo dismantling or mechanical breakup and sorting for hazardous components and valuable materials, followed by mechanical processing. The output materials represent high value, specifically from non-ferrous materials and printed circuit boards (PCBs). Dismantling is conducted by manually dismantling and separating hazardous as well as valuable components. Driven by the high costs of manual labour in Europe, mechanical processing has been developed to replace manual dismantling as much as possible. Here, technologies to break up appliances in a slowly rotating drum (‘smasher’) or to cut up SA (‘cross-flow shredder’), both are followed by a sorting process for the removal of hazardous and valuable components. For the subsequent processing by crushing and separation, a wide spectrum of technologies like hammer mills, magnetic separation, sieves, eddy current separators and other classifiers have been installed and improved in the European recycling industry. Thoroughly applied, these technologies produce high-quality secondary products, mainly metal concentrates as input to metal mills and plastics. Hazardous components and materials that have not been recycled are sent to disposal by incineration, landfilling and hazardous waste treatment. For details of the treatment processes, see Cui and Forssberg [25], Salhofer and Gabriel [26] and others. Table 5 gives an overview of the separation technologies applied mainly for the treatment of end-of-life vehicles, and most of these processes are also applied for e-waste. The effect of dismantling on the separation of hazardous components was analysed for e-waste treatment plants in Austria [28]. Modelling the potential content of components containing hazardous

Table 5 Processes for the separation of materials after fragmentation [27]

Separation techniques	Argonne	Galloo	MBA-polymers	Salyp process	Stena	R-plus	VW-Sicon
Air classification	X	X	X	X	X	X	X
Magnetic separation	X	X	X	X	X	X	X
Eddy current separation	X	X	X	X	X		X
Screening		X		X	X	X	X
Trommel separation	X	X		X	X		X
Optical sorting				X			X
Manual sorting					X		
Drying						X	
Float/sink separation		X		X	X		X
Froth flotation	X						
Thermo-mechanical sorting				X			
Wet grinding			X				
Hydrocyclone			X				
Static, hydrodynamic separation tanks		X					
Heavy media separation					X		

substances in the input material and comparing them to the output of the plants led to removal rates for selected components of 50–70%, demonstrating the limitation of manual dismantling on a case study basis.

A typical treatment sequence for e-waste in Europe, based on Wäger et al. [29], comprises the following steps: after collection and transport, the end-of-life products reach the recycling facility, where sorting, dismantling and mechanical processing take place. The output materials are either ready for end processing (e.g. steel and aluminium scrap) or undergo further treatment steps (e.g. mixed materials, cables, plastics, PCBs and CRTs). In the subsequent treatment, compound materials ('metal and/or plastic mix') such as motors, coils, etc., and cables are further processed mechanically to separate different materials (metals from plastics and non-ferrous metals from ferrous metals). This task is often assigned to specialised treatment companies. CRT screens are separated into front and neck glass, and the fluorescent powder is removed. Batteries from dismantling are sent to specialised battery recycling facilities. Other waste (wood from cabinets, insulation materials, hazardous materials, etc.) is sent to disposal (see Fig. 1).

Printed circuit boards harvested from the dismantling are traded and sent to specialised metallurgic treatment facilities. Within Europe there are three plants (Aurubis, Boliden, Umicore) which apply different smelting processes, followed by other steps such as hydrometallurgy. These special smelters achieve high recycling rates, for example, Umicore claims recycling rates for precious metals of more than 95% [30]. Plastics from dismantling and – to a larger extent – from mechanical processing undergo sorting (sensor based sorting, heavy media separators, among

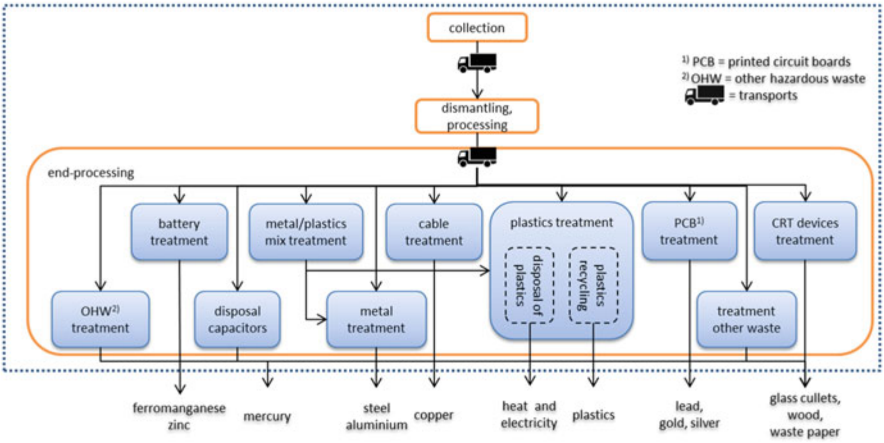

Fig. 1 E-waste treatment technologies in Europe (schematically, based on [29])

others), and then go into materials recycling, or are incinerated or disposed of in landfills, respectively.

Some challenges in the future will be to level the standards for technology as well as for monitoring in the EU member states. As a directive, like the European WEEE II Directive [7], it sets only a framework. National implementation will vary and produce unfair competition, favouring low-cost technology with lower material yields.

4.2 *Treatment in China*

From the 1980s onward, China has imported increasing amounts of e-waste from the USA, Europe and other regions for recycling (cf. [31]). The driving force was the growing demand for resources in a rapidly growing production industry, which could cover the material demand partly through recycling. In some areas, most prominently in Guiyu (Guangdong province), large capacities for e-waste treatment have been developed. In Guiyu at its peak period in 2011, up to 150,000 people worked in recycling [32]. Geeraerts et al. [33] estimate the import quantity a high as 8 mt/year. Without regulations, neglecting the partly hazardous nature of the material and following the principle of lowest cost, highly polluting practices are established. Sepúlveda et al. [34] describe typical e-waste treatment techniques and processes in China and India. These techniques include the open burning of PCBs, cables and plastics and the burning of PCBs to separate the components of recovered solder and leaching and the amalgamation of PCBs to recover precious metals. The emissions from these processes include, among others, lead, PBDEs, dioxins and furans and are found in several outputs such as particulate matter, fumes, ashes and liquid emissions (effluents) from dumping activities, as well as from hydrometallurgical processes (leaching, amalgamation). High concentrations have been identified in air pollution, solid residues, dust and soil, as well as in water and sediments. The values exceed comparison values, e.g. for lead in the WHO Drinking Water Guidelines [35], by several orders of magnitude and show the pollution in the environment as well as health and safety threats for workers and residents.

Along with the establishment of recent legislation for the treatment of e-waste (cf. [36]) and supported by a subsidies program, large capacities for e-waste treatment have been developed. By mid-2015, 106 recycling plants were included in the China e-waste funding scheme, and treatment has reached a volume of 1,458 mt in 2014 [37], compared to an estimated generation of 6.0 mt [8]. In the course of the last 3 years (2012–2015), 12 recycling facilities situated along China's East coast have been visited [19]. Eleven of these facilities mainly dismantle appliances, and some have subsequent treatment steps. Only one of these facilities focusses explicitly on the treatment of materials from dismantling, i.e. cables and PCBs.

Concerning the range of product types processed, 7 of the 11 dismantling facilities cover all 5 product types under regulation (CRT TV sets, refrigerators, air conditioners, PCs and washing machines), while the rest have capacity for some of the products. Two recyclers have established dismantling lines for additional products not covered by the regulations (LCD screens, toner cartridges). The dismantling process is undertaken manually, typically with the aid of conveyor belts, workstations with tools and boxes or shafts for the output materials for dismantling.

For treatment of CRT TV sets, the following steps are applied: After opening the housings and separating housing materials, metal frames, PCBs and cables, the glass body of the screen is split into the front and cone glass, in most cases with hot wire technology, and in one case, laser cutting technology was applied. Then fluorescent powder is sucked off.

In most cases, refrigerators and air conditioners undergo a two-stage treatment where in the first stage the coolant is extracted and in the second stage the body of the refrigerator is fragmentised in a closed system. In one case, only the second step is applied, i.e. refrigerators directly go into the shredder.

PCs as well as washing machines are dismantled manually. LCD screens (one plant only) are dismantled in an underpressurised cabin to avoid the accidental release of Hg from potentially broken backlight fluorescent lamps, and workers in the cabin wear appropriate safety equipment. After dismantling, the LCD panel is crushed in an enclosed machine. Toner cartridges (one plant only) are fragmentised mechanically, followed by a cleaning step where the toner dust is separated. The ferrous metals, non-ferrous metals and plastics are separated.

The processing of PCBs takes place in eight of the facilities (seven dismantling facilities and one specialist for cables and PCBs), and this treatment is done mechanically (fragmentising and separating materials) with the aim of recovering copper. Three recyclers reported to send the PCBs to mechanical recycling at a specialised plant. Only one recycler operated a hydro- and pyrometallurgic facility, which recovers, in addition to copper, gold and silver. The processes applied are stripping, electrolysis and a refinement of gold through a melting process.

Plastics from dismantling are partly sorted into plastic types and partly fragmentised to reduce the volume for transport into specialised plastic recyclers. No separation of plastics with brominated flame retardants was observed in the plants visited. Some e-waste recyclers use plastics from dismantling directly for the production of wood plastic compounds.

Figure 2 shows the input into recycling facilities in five provinces (Beijing, Hubei, Zhejiang, Jiangsu and Guangdong), where the above-mentioned recycling plants are located and which were visited as part of the REWIN project [38]. The figure shows the quick increase in treatment capacities from 2010 to 2014 and, secondly, the large proportion of TV sets (80–90% of the mass input) compared to other types of appliances. It is obvious that TV sets are less attractive for informal recyclers compared to product types like PCs, refrigerators or air conditioners, as the latter have a higher share of ferrous, non-ferrous or – for PCs – precious metals.

The main challenge for the treatment of e-waste in China is the variable and partly lacking supply of input material for recycling facilities. Comparing e-waste generation and input to formal recycling facilities makes clear that a larger part of the e-waste still does not end up in the formal recycling industry but probably undergoes informal treatment practices. For the established formal recycling facilities, the processing of PCBs and plastics poses challenges, as PCBs are mainly processed mechanically, leading to a loss of precious metals, and plastics are typically not separated into materials containing (brominated) flame retardant and those free of flame retardants.

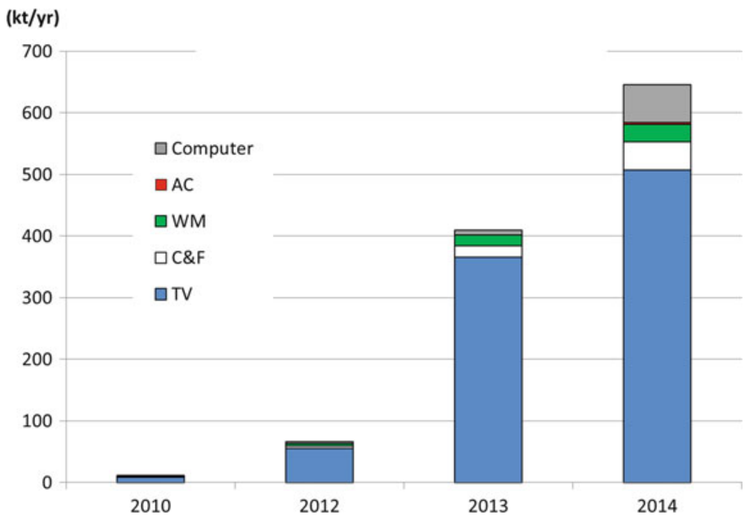

Fig. 2 Treatment quantities in five Chinese provinces 2010–2014 [38]

4.3 Treatment in Vietnam

Besides recycling to recover materials, reuse and repair play an important role in the management of e-waste in Vietnam. After being collected, the appliances are classified by collectors, repairers and service shops. The appliances undergo a thorough repair or refurbishment process and then are sold in second-hand markets. The repair and service shops disassemble useable components for reuse, and only appliances which are impossible to repair or do not pay off the cost of the repair will be transferred to dismantling workshops. At those workshops, reusable parts (transistors, chips, parts) are collected for selling to repairers and service shops for part replacement during repair work.

The following step of dismantling is undertaken to separate materials and prepare them for further processing. In Vietnam, this step typically takes place at 'craft villages', which are villages with a profession different from agricultural activities, creating income for the habitants. Thus, craft villages play an important role in rural economic development, as they provide work for residents of neighbouring villages. Twenty seven percent of farm households earn income from both farming and other careers, while thirteen percent of rural households are professionally engaged in careers other than farming [39]. They have also attracted about ten million full-time workers, representing approximately 30% of workers in rural areas (cf. [40]). The e-waste treatment was counted for approximately 30 craft villages handling e-waste recycling out of 90 waste recycling villages, mainly in the north of Vietnam, from a total of more than 3,000 craft villages in Vietnam [23]. At those villages, e-waste is dismantled and sorted manually into components by workers working with no or with a low level of protective equipment. Workshops at e-waste dismantling craft villages have been specialised by types of appliances. For example, some workshops only buy and dismantle refrigerators and washing machines, some only collect CD and DVD players, and some are in charge of plastic collecting and grinding. After dismantling, the tradable parts are classified for further treatment or sale. Risky processes, like the open burning of copper wires to extract copper or the chipping and melting of mixed plastics, are widely used, and the residues from these processes are discharged into fields, riverbanks or ponds.

The current situation of e-waste treatment has led to many serious risks related to the environment and human health, not only of the workers at those workshops but also for residents living close to workshops. The analysis of Tue et al. [41] showed the accumulation of polychlorinated biphenyls and brominated flame retardants in breast milk from women living in e-waste recycling sites (Bui Dau in Hung Yen province) at very high levels of polybrominated diphenyl ethers and hexabromocyclododecanes. Tue et al. [42] found the polychlorinated biphenyl and brominated flame-retardant contaminants in indoor dust and air at informal e-waste recycling site to be significantly higher than in urban house dust. The soil near workshops and open burning places was contaminated by flame retardants from e-waste recycling (cf. [43]). Dioxins, originating from high-temperature processes in e-waste recycling, such as open burning of copper wires and plastic recycling process using conventional extruders [44], were concentrated.

It is difficult to estimate, monitor and record how much e-waste is transported to and processed at craft villages in Vietnam. The data on e-waste is rough, and based on estimates from interviews with people from craft villages, experts and traders in the field, it is impossible to clarify the situation with certainty. More details about processes applied in e-waste treatment in Vietnam can be found in Tran and Salhofer [23].

The main challenges are both the heavy environmental pollution from uncontrolled processes and health threats to workers and the residents of craft villages.

5 Conclusions

From the wide range of products covered, e-waste is one of the most complex waste streams. The properties of the different e-waste categories imply that a number of technologies are required to cover the whole range of products. The level of legislation and implementation varies significantly between regions and countries.

In Europe, e-waste management has been developed from existing structures in municipal waste management, mainly organised by municipalities. 3.2 mt from a generation mass of 9 mt were collected in 2014. The challenges are:

- To intensify collection and to confine illegal exports
- To establish uniform technical and monitoring standards for treatment throughout EU member states

For a long time in China, the informal sector was dominated by both the collection and treatment of e-waste. After recent legislation and public funding, large (formal) treatment capacities have been developed, while, lacking formal alternatives, collection is still dominated by the informal sector. From a generated mass of 6.0 mt, in 2013, 1.3 mt were collected for recycling. Challenges are:

- The need to improve labour conditions and the social security of informal collectors
- The lack of input to recycling facilities due to the strong competition with the informal recycling sector
- Technology for the treatment of PCBs and plastics

In Vietnam, both collection and treatment are in the hands of the informal sector; unsafe practices and environmental hazards are consequences. Challenges are:

- To improve the labour conditions of informal collectors
- Environmental pollution as well as health threats from uncontrolled processes

References

1. EU (2002) Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE). http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32002L0096. Accessed 7 Jan 2017
2. OECD (2016) Extended producer responsibility: updated guidance for efficient waste management. OECD Publishing, Paris. doi:10.1787/9789264256385-en
3. OECD (2001) Extended producer responsibility: a guidance manual for governments. OECD Publishing, Paris. doi:10.1787/9789264189867-en
4. Huisman J, Magalini F, Kuehr R, Maurer C, Ogilvoe S, Poll J, Delgado C, Artim E, Szlezak J, Stevels A (2007) Review of Directive 2002/96 on Waste Electrical and Electronic Equipment (WEEE). Final report. http://ec.europa.eu/environment/waste/weee/pdf/final_rep_unu.pdf
5. Salhofer S, Spitzbart M, Maurer K (2012) Recycling of flat screens as a new challenge in WEEE recycling. Waste Resour Manage 165:37–43
6. Salhofer S, Spitzbart M (2009) Modelling of mechanical treatment of WEEE. In: Proceedings of the 3rd BOKU waste conference, Vienna, pp 143–150
7. EU (2012) Directive 2012/19/EU on waste electrical and electronic equipment. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32012L0019. Accessed 7 Jan 2017
8. Baldé CP, Wang F, Kuehr R, Huisman J (2015) The global e-waste monitor – 2014. United Nations University, IAS – SCYCLE, Bonn, Germany. http://i.unu.edu/media/unu.edu/news/52624/UNU-1stGlobal-E-Waste-Monitor-2014-small.pdf
9. Borregaard J (2013) Experiences from WEEE collection trials in Copenhagen. Presentation at ISWA Beacon conference, Düsseldorf, Nov 2013
10. Salhofer S (2014) Small, but powerful – why we should put more emphasis on the collection of small WEEE. In: Proceedings SUM 2014, second symposium on urban mining, Bergamo, Italy
11. Sander K, Schilling S (2010) Optimierung der Steuerung und Kontrolle grenzüberschreitender Stoffströme bei Elektroaltgeräten/Elektroschrott. Umweltbundesamt, Deutschalnd. http://www.umweltbundesamt.de/publikationen/optimierung-steuerung-kontrolle. Accessed 7 Jan 17
12. Chung SS, Zhang C (2011) An evaluation of legislative measures on electrical and electronic waste in the People's Republic of China. Waste Manag 31:2638–2646
13. Hicks C, Dietmar R, Eugster M (2005) The recycling and disposal of electrical and electronic waste in China – legislative and market responses. Environ Impact Assess Rev 25:459–471
14. Qu Y, Zhu Q, Sarkis J, Geng Y, Zhong Y (2013) A review of developing an e-waste collection system in Dalian. J Clean Prod 52:176–184
15. Yu J, Williams E, Ju M, Shao C (2010) Managing WEEE in China: policies, pilot projects and alternative approaches. Resour Conserv Recycl 54:991–999
16. Liu D, Shen Y (2012) Second report of a report series on the development trend of the renewable resource industry: report on the development trend of the WEEE industry (in Chinese). Internal company report, Beijing, pp 2–21
17. Wang F, Kuehr R, Ahlquist D, Li J (2013) E-waste in China: a country report. Step green paper series 10–47. http://isp.unu.edu/publications/scycle/files/ewaste-in-china.pdf
18. Zhong W (2010) WEEE collection management process and legislative institutional build-up (in Chinese). Policy Innov Stud 3:41–56
19. Salhofer S, Steuer B, Ramusch R, Beigl P (2016) WEEE management in Europe and China – a comparison. Waste Manag 57:27–35
20. Yang J, Lu B, Xu C (2008) WEEE flow and mitigating measures in China. Waste Manag 28 (2008):1589–1597
21. Wang Z, Zhang B, Yin J, Zhang X (2011) Willingness and behavior towards WEEE recycling for residents in Beijing city. Chin J Cleaner Prod 19:977–984
22. Baum J (2011) Background, basic concepts and overview on circular economy in China and Europe. In: Weigelin-Schwiedrzik S (ed) Re-sourcing in China: standards for circular economy – comparing China and the EU. Project report. Jubilee Fund of the Austrian Central Bank Project No. 13987, Vienna

23. Tran CD, Salhofer S (2016) Analysis of recycling structures for e-waste in Vietnam. J Mater Sci Waste Manage 2016:1–17
24. Duc-Quang N, Yamasue E, Okumura H, Ishihara KN (2006) Wastes of electronic and electric equipment (WEEE) recycling system in Vietnam: a case study on copper recycling. In: Proceedings of the second joint international conference on Sustainable Energy and Environment (SEE 2006), vol 2, Bangkok, Thailand
25. Cui J, Forssberg E (2003) Mechanical recycling of waste electric and electronic equipment: a review. J Hazard Mater B99:243–263
26. Salhofer S, Gabriel R (2000) Mechanical processing or co-firing? Treatment of end-of-life electrical and electronic equipment from a waste management point of view. In: Proceedings of electronics goes green, Berlin, Germany
27. Vermeulen I, Van Caneghem J, Block C, Baeyens J, Vandercasteele C (2011) Automotive shredder residue (ASR): reviewing its production from end-of-life vehicles (ELVs) and its recycling, energy or chemicals valorisation. J Hazard Mater 190:8–27
28. Salhofer S, Tesar M (2011) Assessment of removal of components containing hazardous substances from small WEEE in Austria. J Hazard Mater 186:1481–1488
29. Wäger PA, Hischier R, Eugster M (2011) Environmental impacts of the Swiss collection and recovery system for waste electrical and electronic equipment (WEEE): a follow up. Waste Manag 409:1746–1756
30. Hagelueken C (2012) Recycling the platinum group metals: a European perspective. Platin Met Rev 56:29–35
31. Steuer B (2016) What institutional dynamics guide waste electrical and electronic equipment refurbishment and reuse in urban China? Recycling 1:286–310. doi:10.3390/recycling1020286
32. Steuer B (2015) Informelle EAG Behandlung im südchinesischen Guiyu - eine Feldstudie. Presentation at University of Natural Resources and Life Sciences, Vienna, 29 Oct 2015
33. Geeraerts K, Illes A, Schweizer JP (2015) Illegal shipment of e-waste from the EU. A case study on illegal e-waste export from EU to China. A study compiled as part of the EFFACE project. http://efface.eu/. Accessed 7 Jan 2017
34. Sepúlveda A, Schluep M, Renaud F, Streicher M, Kuehr R, Hagelueken C, Gerecke AC (2010) A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipment during recycling: examples from China and India. Environ Impact Assess Rev 30:28–41
35. WHO (2011) Guidelines for drinking-water quality, 4th edn. World Health Organisation. http://www.who.int/water_sanitation_health/publications/2011/dwq_guidelines/en/. Accessed 7 Jan 17
36. Zeng X, Li J, Stevels A, Liu L (2013) Perspective of electronic waste management in China based on a legislation comparison between China and the EU. Waste Manage J Cleaner Prod 51:80–87
37. Hu H (2015) Policy and development thinking of electronic waste management. Presentation at the Shanghai IE Expo Summit Forum, 7 May 2015
38. Zhang M, Hou Q, Luo Q, Wu Y, Deng C, Steuer B (2015) WEEE recycling rates in REWIN target provinces – progress report 2012-2015. REWIN Project report 2015. http://www.rewin-china.net. Accessed 7 Jan 17
39. URENCO (2007) The development of E-waste inventory in Vietnam. Urban Environment One Member State-Owner Limited Company, Hanoi, Vietnam
40. MONORE (2011) Vietnam national environment report. Ministry of Natural Resource and Environment, Vietnam. http://archive.basel.int/techmatters/e_wastes/E-waste%20Inventory%20in%20Vietnam.pdf
41. Tue NM, Sudaryanto A, Minh TB, Isobe T, Takahashi S, Viet PH, Tanabe S (2010) Accumulation of polychlorinated biphenyls and brominated flame retardants in breast milk from women living in Vietnamese e-waste recycling sites. Sci Total Environ 408:2155–2162
42. Tue NM, Takahashi S, Suzuki G, Isobe T, Viet PH, Kobara Y, Seike N, Zhang G, Sudaryanto A, Tanabe S (2013) Contamination of indoor dust and air by polychlorinated

biphenyls and brominated flame retardants and relevance of non-dietary exposure in Vietnamese informal e-waste recycling sites. Environ Int 51:160–167
43. Someya M, Suzuki G, Ionas AC, Tue NM, Xu F, Matsukami H, Covaci A, Tuyen LH, Viet PH, Takahashi S, Tanabe S, Takigami H (2015) Occurrence of emerging flame retardants from e-waste recycling activities in the northern part of Vietnam. Emerging Contam 2:58–65
44. Tue NM, Takahashi S, Subramanian A, Sakai S, Tanabe S (2013) Environmental contamination and human exposure to dioxin-related compounds in e-waste recycling sites of developing countries. Environ Sci: Processes Impacts 15:1326–1331

Part III
Resource and Climate Protection Effects

The Waste Management System in China and Greenhouse Gas Emission Inventories

Lou Ziyang, Xing Zhilin, Cheng Zhaowen, Zhao Tiantao, and Cai Bofeng

Abstract The increase in waste generation amounts and its Greenhouse gas (GHG) emissions are two main pressures for the Chinese government. The development process of the waste management system was summarized. The corresponding GHG emissions pattern was studied, and the potential reduction measurements were also proposed based on the different steps for the waste management system. It was found that the total estimated GHG increased from 10.95 million tons (1991) to 72.4 million tons CO_2-equiv (2013) on the basis of the IPCC methods. Landfill was the main GHG source, as the corresponding percentage increased to the peak of 82% (1999) and finally to 69.5% (2013) in the period studied. Eastern China was the dominant CO_2 emission region, while the percentage decreased from 39.6% (2003) to 26.4% (2013). To get more detailed GHG emissions from landfills, the bottom-to-top method was applied to estimate the corresponding emissions and reduction potential from 1,955 landfills in 2012. The source reduction in MSW and the diversion alternatives for landfills are indirect, while useful GHG mitigation way for the reduction of the terminal disposal amounts and its GHG emissions through the implementation of "pay-as-you-throw" and an environmental protection tax.

L. Ziyang (✉)
School of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai, China
e-mail: Louworld12@sjtu.edu.cn

X. Zhilin and Z. Tiantao
Chongqing University of Technology, Chongqing, China
e-mail: 229200985@qq.com; Zhaott@cqut.edu.cn

C. Zhaowen
Shanghai Jiao Tong University, Shanghai, China
e-mail: Chengzhaowen@126.com

C. Bofeng
Chinese Academy for Environmental Planning, Beijing 100012, China
e-mail: Caibf@caep.org.cn

R. Maletz et al. (eds.), *Source Separation and Recycling*,
Hdb Env Chem (2018) 63: 247–268, DOI 10.1007/698_2017_32,
© Springer International Publishing AG 2017, Published online: 2 June 2017

Keywords GHG emission, GHG reduction, Methanotrophs, Source separation, Waste sector

Contents

Abbreviations

EC	Eastern China
FOD	First-order decay model
IPCC	Intergovernmental panel on climate change
LCF	Landfill gas collection and flaring
LCSR	Landfill cover soil reactor
LFG	Landfill gas
MC	Middle China
MHDC	Ministry of Housing and Urban-Rural Development of the People's Republic of China
ML	Mineral landfill
MSW	Municipal solid waste
Mt	Million tons
NC	Northern China
NE	Northeastern China
NMS	Nitrate mineral salts
NW	Northwestern China
OLCS	Original landfill cover soil
PVC	Polyvinyl chloride
RL	Renewable landfill
RPL	Refinement process for MSW landfilling
SC	Southern China
SLCS	Simulated landfill cover soil
SW	Southwestern China

1 The Waste Sector in China

With the rapid development and the urbanization process, waste generation has increased greatly. The waste generation rate relies greatly on the population, its living habits/levels, and the urbanization process. China, as the most populous (22% of the global population) and fastest growing emerging country in the world, consequently increased its annual municipal solid waste (MSW) generated from 245 kg per capita in 1991 to 275 kg per capita in 2013, and almost ten times the annual MSW of 178.6 million tons was produced in 2014 [1]. The basic waste information in China in 2014 is shown below (Table 1):

It could obviously be observed that around 0.179 billion tons of MSW was collected, and 91.7% has been disposed in a sanitary way, among which 65.4% of total MSW was disposed in a sanitary landfill, and 32.4% was incinerated. The rest was disposed in other ways, such as composting or resource and recycling. However, the waste management system was not well recorded before 1978, when the ministry of housing and urban-rural development of the People's Republic of China (PRC) started to work on for the urban waste system. The official MSW data, including MSW collection and disposal amounts, was compiled and inventoried annually in the China Urban Construction Statistical Yearbook, although the statistical data was not consistent, and inconsistent data in some years was found due to the different statistical caliber and sampling representative. Landfills (including open dumping sites), incineration, and composting have been the three main disposal processes in the past few decades, among which incineration increased very quickly from 47 plants in 2003 to 187 plants in 2014, with almost 100 plants under construction, while composting has been greatly reduced because of the lack of acceptable routes for composting products [1]. Despite many efforts to reduce MSW landfilling and control large landfill emissions, the landfill sector remains the predominant MSW disposal process because of the increasing waste streams in China, which increased from 64.04 million tons of waste from landfilling in 2003 to 107.28 million tons in 2014, according to the statistics data [1]. Even for the megacity of Shanghai, MSW landfilling, including the dumping sites, is still predominant in the whole waste disposal process, with an occupied percentage

Table 1 MSW disposal information in 2014 in China [1]

Collected and transported (10,000 tons)	Number of harmless treatment plants/grounds (units)	Sanitary landfill	Incineration	Other
17,869.09	819	605	187	26
Volume of treated (10,000 tons)	Harmless treatment capacity (tons/day)	Sanitary landfill	Incineration	Other
17,226.68	532,825	334,986	185,157	12,182
Volume of harmlessly treated (10,000 tons)	Sanitary landfill	Incineration	Other	
16,398.62	10,728.21	5,332.99	319.59	

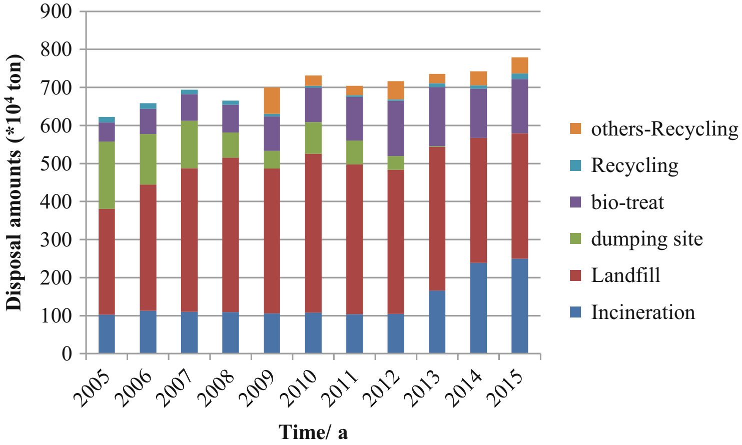

Fig. 1 Basic disposal information for Shanghai over the past 10 years

range of 41.6–73.2%, although MSW incineration has increased quickly over the past 5 years (Fig. 1).

2 GHG Emissions from Waste Sectors

China faces an increasingly complex set of environmental and social pressures for MSW reduction and CO_2 mitigation, especially after joining the Paris Agreement in 2015. Economic growth is the major underlying cause for GHG from diverse human activities, and the waste sector is the main part, since it links our industrial and life activities greatly. Currently, the ever-increasing amount of waste is one of the urgent challenges for modern cities to an extent that most of them have been christened as "cities besieged by garbage." In fact, the waste industry is considered as one of the significant sources of anthropogenic GHG, a matter that is currently of great concern to environmentalists. It has been estimated that the waste sector was the third largest contributor to global emissions of non-CO_2 greenhouse gasses, accounting for 13% of total emissions [2]. MSW properties in China are totally different from those in developed countries, which are characterized as "three high and one low," i.e., high mixture, high inorganic matter content, high percentage of putrescible waste (more than 55% with consequent high moisture), and low calorific heating value [3], since a non-classified waste management system is applied as a waste collection system. Therefore, more CH_4 was released from landfills. The comprehensive and accurate estimation of GHG becomes increasingly important step for the achievement of the GHG reduction target.

The activity data for individual waste treatment facilities were based on the national waste treatment facilities' sanitary level assessment projects led by the Ministry of Housing and Urban-Rural Development, carried out in China in 2006, 2009, and 2012 [4, 5]. Emissions factors, such as the critical factor of R, were chosen based on the national landfill assessment results of 2006, 2009, and 2012, and $t_{1/2}$ was set according to our lab experiments and waste composition [6–8]. The first-order decay (FOD) model recommended by Intergovernmental Panel on Climate Change (IPCC) guidelines has been applied for GHG emission from landfills.

Waste composition and the relative key parameters were the critical factors for the GHG emissions calculation, and the operation parameters, such as correction factor, CH_4 content, CH_4 recovery rate and oxidation factor in landfills, burning efficiency in incineration plants, and CH_4 and N_2O generation rate in composting, were the combined results from the field investigation, laboratory analysis, literature review, and the experts' judgment. GHG emissions were calculated by multiplying the MSW disposal in different facilities with its respective emissions factors in IPCC methods. The total GHG emissions from the waste sector were aggregated based on the individual values from each treatment process and finally normalized into CO_2-equiv value.

$$CO_{2\,\text{landfill}} = CO_{2\,\text{sanitary landfill}} + CO_{2\,\text{open dumping sites}}$$

$$CO_{2\,\text{incineration plant}} = CO_{2\,\text{incineration plant}} + CO_{2\,\text{open burning}}$$

$$\text{Total GHG emission} = CO_{2\,\text{landfill}} + CO_{2\,\text{incineration plant}} + CO_{2\,\text{composting}}$$

3 China's Contribution for GHG Emissions from Waste Sector

3.1 GHG Pattern from the Waste Sector

The GHG emissions from the MSW sector in China from 1991 to 2013 are represented in Fig. 2.

The CO_2 emissions from the MSW sector gradually increased from 10.95 million tons (1991) to 72.40 million tons (2013) over the last decade. The CO_2 emission patterns vividly indicated that China experienced tremendous MSW generation growth after 1991 with the expanding of the MSW collection area and more and more large-scale modern treatment facilities becoming operational. Based on the bottom-up methods, total CH_4 emissions of 1.48 million tons were estimated from 1955 landfills in 2012, 24.88% higher than that those in 2007 [6]. It could be inferred that landfills were the main contributors. A small number of sanitary landfill sites were either under construction or operational, but at the same time, the amounts of large-scale unsanitary or semi-sanitary landfills sites increased from less than twenty (1990) to thousands in number (in 2000), and the burgeoning

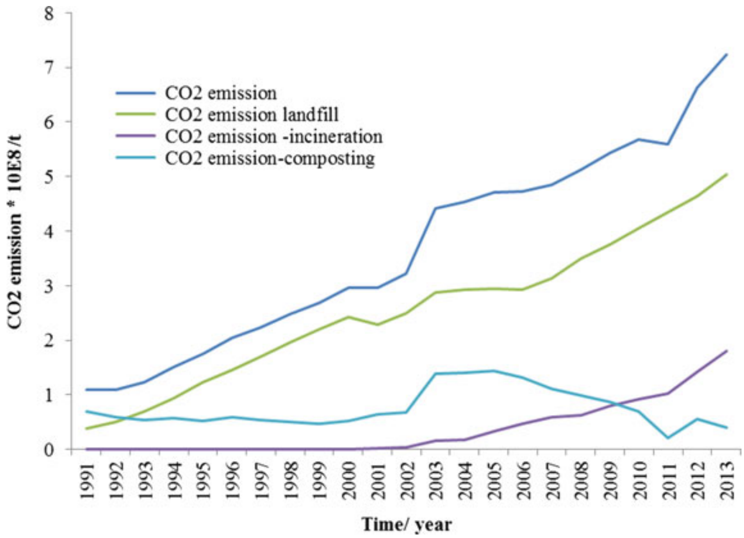

Fig. 2 Variations in CO_2 emissions from the MSW sector in China from 1991 to 2013

unsanitary landfills caused rapid growth in CO_2 emissions. It is a delight to find that the unsanitary landfills were supposed to be closed, and modern large-scale sanitary landfills were promoted after 2003. It can be found that only 143.4 kg of CO_2 emissions per ton of waste disposal were released in 1991, while it increased to 297.2 kg in 2003 and 420 kg in 2013. This discrepancy owes to the fact that old MSW accumulated in a landfill contributes to a large amount of CO_2 emissions, which resulted in the higher CO_2 emissions in the later period of observation time. Compared to the CO_2 emissions from the MSW sector, the incremental tendency of the waste generation rate was found to be a little slow, from 0.245 tons annually/cap. in 1991, 0.284 tons annually/cap. in 2003, and then decreasing to 0.236 tons annually/cap. in 2013. The increase in the urban population, rapid urbanization process in the western region, and the different statistical caliber might result in the decrease in the national MSW generation rate after 2006 [9].

3.2 Regional Distribution of the GHG Pattern

The temporary and spatial distribution of CO_2 emissions from the MSW sector in seven regions are shown in Fig. 3.

It was observed that total CO_2 emissions from MSW sectors showed an increasing trend in past decades, especially in the period from 2003 to 2008, because of the rapid construction and operation of MSW treatment facilities and the regional disparity patterns that were also observed. A notable increment of total CO_2 emissions was observed in the EC, SC, and SW regions, and around 1.2–1.7

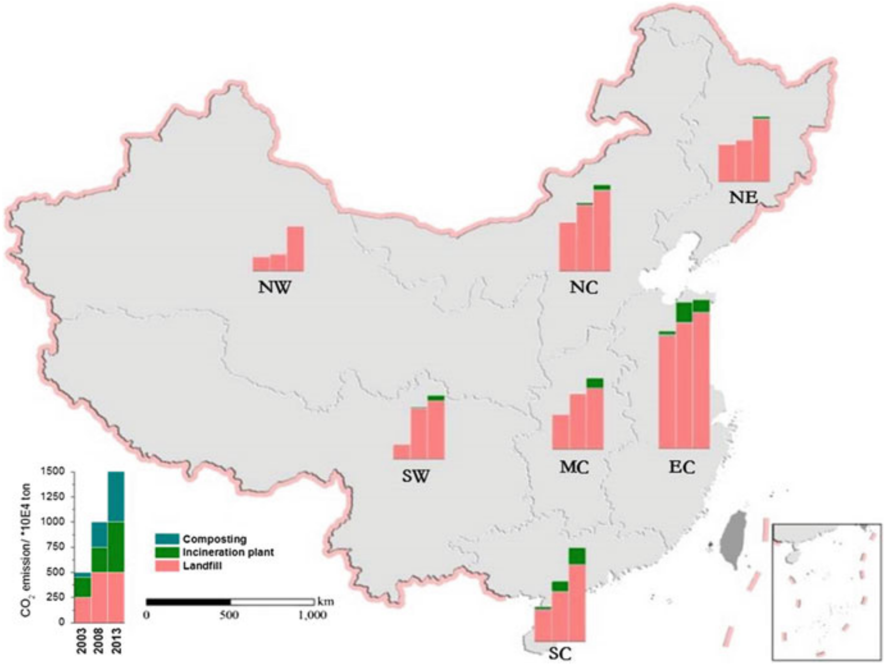

Fig. 3 Total amounts and individual CO_2 emissions from waste sectors in seven regions. The first, second, and third columns from the left to right show the GHG emissions released in 2003, 2008, and 2013, respectively. The columns consist of three sub-columns with different colors, which signify the GHG emissions from landfills (*pink*), incineration plants (*green*), and compositing (*blue*). Note: *NC* North China, *NE* North East, *EC* East China, *MC* Middle China, *SC* South China, *SW* South West, *NW* North West

times and 1.6–2.7 times higher CO_2 emissions in 2008 and 2013 were reported, respectively. A sharp increase of 3.4 times and 4.2 times higher CO_2 emissions was observed in the SW in 2008 and 2013, followed by NW, with 3.15 times higher each, compared to the base year of 2003. The possible reason was a dearth of MSW disposal treatment facilities in the NW and SW before 2003, and more and more waste disposal facilities put into operation. As a consequence of that, there was a sharp increase in CO_2 emissions, since the non-hazardous waste disposal rate of over 80% was the basic requirement for the local government to apply to the state level as a healthy city. The SW region had a maximum increase in the waste disposal rate, at 3.4 times higher than that of 2003, followed by the SC and MC regions, with 1.73 and 1.60 times higher each. A rapid rise in CO_2 emissions occurred between 2008 and 2013 in the NW, at 3.15 times higher compared to that in 2003.

EC contributed almost one-third of national CO_2 emissions from the waste sector in the last 10 years due to its high population density and living standard and had peak CO_2 emissions of 23.68, 29.58, and 33.20 million tons of CO_2 in years

2003, 2008, and 2013, respectively. However, the occupied percentage decreased from 38.6% (2003) to 30.7% (2013), because CO_2 emissions from other regions experienced a dramatic increase in the same period, with more MSW disposal facilities operated, such as landfills.

The highest CO_2 emissions from landfills were recorded in 2003 at 96.8%, then onward, a decreasing trend of 91.8% was observed in 2008, and in 2013, it reached 84.7%. More incineration plants came into existence after 2002. For the GHG emissions from landfills in individual regions, it decreased sharply in the EC from 96.1% to 71.9% and in the SC and MC declined from 91.7% to 81.8% and 98.9% to 85.7% from 2003 to 2013, respectively. Generally, a high economic level and limited land for landfill sites were the main causes of these changes, since the construction and operational investments in incineration plants were normally two times higher than that of a landfill. CO_2 ranked as the largest pollutant emitted with 10.687 million tons in 2013, and around 46% of total MSW collection was incinerated in the EC. The percentage of incineration plants increased from 3% (2003) to 14% (2008) and finally reached 28% (2013). It was noticed that only 28% of GHG emissions were from incineration plants in the EC, indicating that less GHG emissions per ton of waste disposal were released from incineration plants. For CO_2 emissions from composting plants, the maximum of 1.0% CO_2 emissions was recorded in 2003 in the MC region, which further decreased to 0% in 2013 due to discontinuing the operation of the composting plants. Therefore, landfill and incineration were the two main sources for the CO_2 emissions. The increase in disparity trends was observed between the period of 2003–2008 and 2008–2013 in these different regions. It was observed that the CO_2 emissions per capita varied in 2003 from the different regions, while the disparity in 2013 decreased. With these results, it could be inferred that many treatment facilities in operation applied some efficient mitigation methods in the past 10 years, such as landfill gas collection and utilization, CO_2 capture from the flue gas in the incineration plant, and high efficient aeration facilities used in composting.

Since landfills are the main contributors of GHG emissions from waste sectors, the spatial distribution of CH_4 emissions from landfills in 2012 is shown in Fig. 4. Total CH_4 emissions reached 1.48 million tons in 2012, 24.88% higher than in 2007 [6]. Eastern China, southern China, and northern China are the first three main contributors, with annual CH_4 emissions of 48.89, 21.90, and 18.38 $\times$ 10^4 tons of CH_4, which comprised around 33.00, 14.79, and 12.41% of total CH_4 emissions from landfills in series. The maximum CH_4 emissions were found in eastern China, with the highest GDP value of 2087.81 billion RMB in 2012. The lowest GDP value of 318.44 billion RMB was found in northwestern China, and the lowest CH_4 emissions of 12.97 $\times$ 10^4 ton were released. Population will influence the CH_4 generation rate, while the different tendency was observed in these seven regions. More CH_4 emissions were found in southern China and northeastern China, meaning that CH_4 emissions rely more on the economic level and living habits, instead of the population.

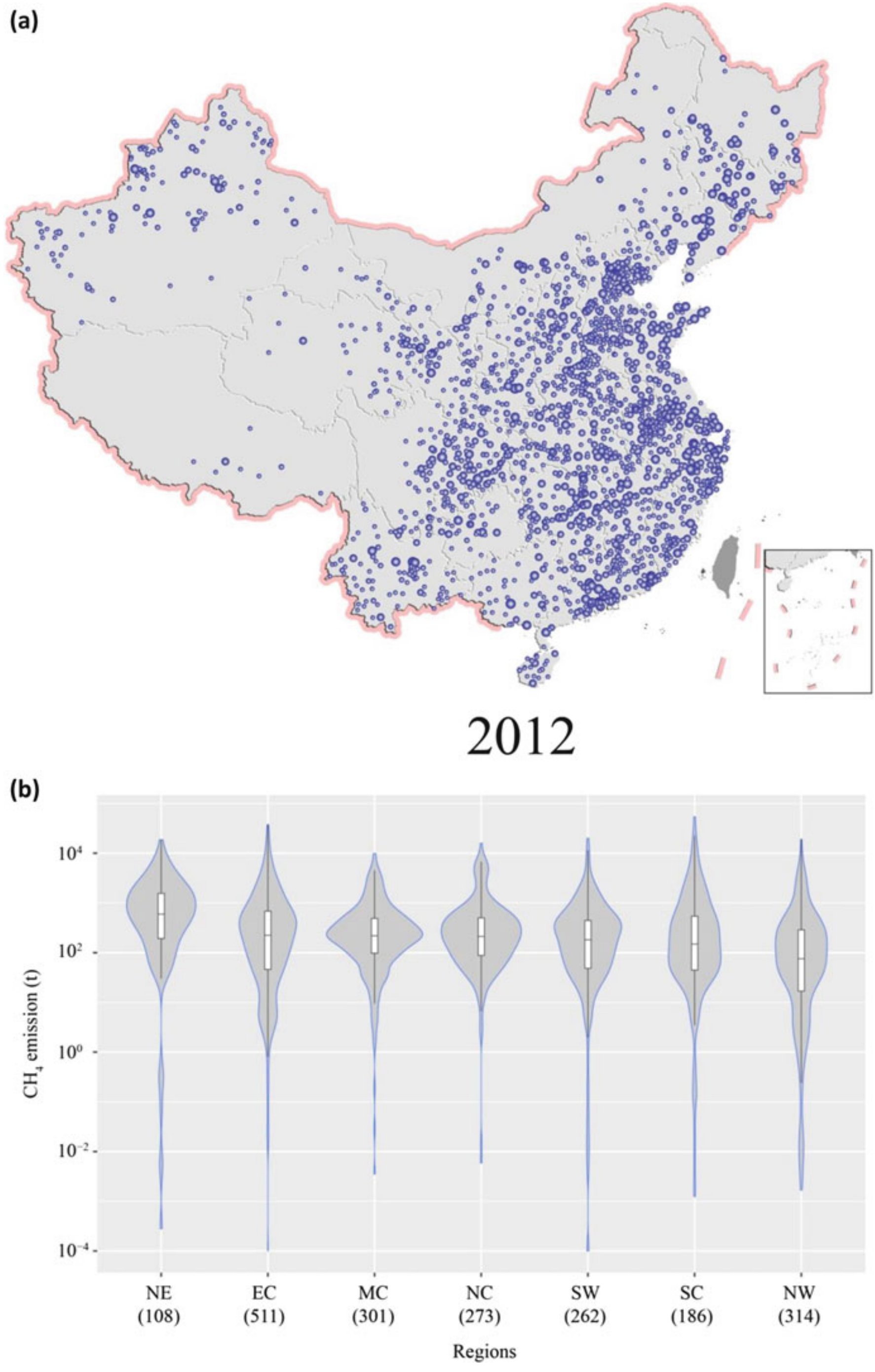

Fig. 4 The CH_4 emission pattern from landfills in 2012. (**a**) The detailed CH_4 emissions; (**b**) The distribution of CH_4 emissions in seven regions

From Fig. 4b, we can see that CH_4 generation amounts rely on the landfill scales greatly, and some large-scale landfills produced more than 10,000 tons of CH_4 per year, while some small-scale landfills might produce less than 10 tons. In 2012, around 45.88% of CH_4 was generated from level I landfills, and 25.77 and 28.35% of CH_4 were released from level II and III landfills, respectively. Different generation patterns were observed in seven regions. The mean values of the CH_4 generation amounts from landfills in all regions, except in the NW, were above 100 tons, and landfills in the NE have the maximum mean value of 594 tons, where more than 75% of landfills produced more than 100 tons of CH_4 annually in the NE. For the MC and NC, half of the landfills generated CH_4 in the range of 100–1,000 tons, meaning that these landfills were of similar scales and operational conditions. The maximum CH_4 emissions from landfills were found in the SC and EC regions, where some landfills generated more than 10,000 tons of CH_4. A varied dispersion of CH_4 emissions was observed in landfills in the SW and NW regions, since the landfill scales in these two regions were more heterogeneous.

Most CH_4 was released from level I landfills in the EC, SC, and NC, with 53.5, 66.4, and 44.0% of total CH_4 emissions, meaning that most of landfills in these areas are large-scale landfills due to the heavy pressure from MSW disposal requirements, and CH_4 utilization or mitigation measurements could be conveniently applied. The core CH_4 emissions area concentrated in the areas of Beijing Tianjin, Shanghai-Shaoxing-Ningbo, and Guangdong-Dongguan-Qingyuan, which is the developed area in China with the mature urbanization process. For the other areas, CH_4 emissions were mostly from the level II and III landfills, especially for the SW, MC, and NW, where around 41.5, 34.0, and 31.0% of CH_4 are released from level III landfills, suggesting that more low-tech CH_4 control methods, such as biocovers, might be the suitable CH_4 control option. Meanwhile, there were more small-scale landfills in these two regions, and around 25% of landfills released less than 10^{-4} tons of CH_4 annually.

4 GHG Abatement Measures from Waste Sector

GHG abatement measures should be considered and applied in the waste sector, and mitigation technologies and diversion alternatives were two promising methods [2], which the former could be used to capture and destroy the GHG generated from landfills and other facilities and the later could be used to reduce the waste generation rate at the source.

4.1 Policy Analysis

GHG emissions from landfills rely greatly on the waste disposal amounts, and the source reduction of MSW is the basic principle through reduction, recycling, and reuse. China has introduced a series of policies to facilitate MSW management.

A long-term strategy for diverting MSW away from landfills and increasing recycling should be created and implemented in China [2], and the government's respond for the constitution of the long tradition for developing waste strategies and plan on the national level. The requirement of MSW pretreatment before landfilling combined with other management activities, such as producer responsibility [10], have been proven to be the strong drivers in diverting MSW away from landfills and toward recycling, which would be useful for the reduction of organic matter landfilling and CH_4 emissions from landfills. The increase in R&D investment should be implemented and stimulated to improve the mitigation technologies and diversion alternatives in the waste sector in China [11].

From the Chinese government side, the Ministry of Housing and Urban-Rural Development of China should try to include the polluter pays principle (PPP) in the waste management system and the new Municipal Solid Waste Management Rule that was released on April 10, 2007, which emphasized the principle of "the person who produces the waste has a responsibility to its corresponding disposal." Many developing countries have extended the PPP to show the obligation of the state for compensating the victims of environmental pollution. In China, the government makes the most dominant contribution to MSW disposal. Moreover, the MSW disposal fee is supposed to be charged according to the cost of MSW disposal and the income level of citizens, often known as the quota system. However, the quota system seems to have a limited contribution to MSW reduction. This phenomenon can be attributed to the fact that the fee charged for MSW disposal is not directly influenced by the volume of MSW it produces. In Europe, effective economic incentives are provided to encourage residents to reduce and recycle MSW. Specially, pay-as-you-throw (PAYT) schemes are a variable pricing mechanism from municipalities in which households are charged according to the quantity of non-recyclable waste they generate and corresponding services of MSW disposal they receive. Considering that PAYT schemes are a cost-effective way to manage MSW and stimulate recycling, this measure has already been widely conducted in Europe, Japan, and the USA. Reports have also shown that countries making effective economic incentives have better performance on MSW recycling and reduction. Notably, proper MSW classification is the premise for achieving the effective management of MSW due to its significant contribution to resource recycling. Previous research has indicated that the level of public awareness has a significant influence on the effectiveness of MSW management. Hussain et al. [12] suggest that residents should be educated in schools and colleges to improve their public awareness toward the proper classification and reduction of MSW. Therefore, effective economic incentives and environmental education to improve public awareness toward MSW classification and reduction at the household level are highly suggested to improve GHG reduction potential.

The "Opinions on Further Strengthening the work of MSW disposal" was approved by the State Council of China on April 19, 2011. This report emphasizes that the resource utilization of MSW (including MSW for energy and recycling) should be further developed. MSW for energy includes energy recovery from the direct combustion of MSW (e.g., incineration, pyrolysis, and gasification) and the production of combustible fuels (e.g., methane and hydrogen). This process can both reduce methane emissions generated from landfills and avoid the CO_2 emissions generated from coal-based electricity generation, which will mitigate global warming from a long-term perspective. It's obvious that the alternative of MSW-based energy will make a significant contribution to mitigate the serious problem of fossil fuel (e.g., coal) depletion, which currently afflicts the rapid development of China [13]. As part of the Kyoto Protocol's response toward the mitigation of global warming, the Clean Development Mechanism (CDM) has developed rapidly in recent years. One of its dominant objectives is to achieve sustainable development in developing countries by providing funds, advanced technologies, and equipment from developed countries. Especially, most of the CDM projects approved by the National Development and Reform Commission (NDRC) are renewable energy projects. Therefore, the implementation of MSW for CDM energy projects and CCS technologies in these plants is also highly recommended.

4.2 GHG Mitigation Process for Incineration Plants

The separation of a highly calorific light fraction to be used for waste incineration can be achieved by rotating trommel screens with screen sizes of 40 and 80 mm, and over 92% of MSW could be separated from unclassified MSW. Three fractions with a different size range and waste composition, namely, >80, >40, and <40 mm, could be obtained, as shown in Table 2. Only 24.75% of the total MSW is found in the fraction with a mesh size of >80 mm, and the fraction with the mesh size of >40 mm occupies around 45.25% of the total MSW. The fraction to 40 mm of screen underflow is supposed to be landfilled. The application of the >40 mm fraction might be one of the feasibility methods for the sorting operation from an economic and practice perspective thereafter. Some inner materials, i.e., glass and metals, could also be removed simultaneously, with the percentage of 11.59%. The residues of <40 mm will be about 43.2%, and over 80% of the biodegradable fraction was found to be 40 mm screen underflow, while the percentage of organic matter decreased from 70.60 to 45.49% after MSW sorting out the 40 mm screen overflow, and the percentage of main high calorific value contributors (like plastic and paper) increased from 12.8% to 25.84% and 7.3% to 13.78%, respectively. The estimated heating values in raw waste, >40 mm fraction and >80 mm fraction, are 3935.0, 5810.7, and 7283.8 kJ/kg, respectively, and thus the introduction of the larger size fraction might get better combustion performance in the incineration plant.

The environmental impacts before (all MSW was treated by incinerating) and after sorting (MSW of the 40 mm screen overflow was treated by incinerating and that of the 40 mm screen underflow was landfilled) are compared. The GW100 impact from the waste treatment process turned from the impact to the benefit, as the size of the waste decreased from >40 mm to the raw MSW, with the value of −0.0007 PE and 0.002 PE per ton MSW, respectively. CH_4, CO_2, and CO are the

Table 2 The distribution of waste composition in different size ranges (%)

Composition	>80 mm	40–80 mm	>40 mm	Raw MSW
The percentage	24.75%	20.05%	45.25%	100
OM	27.51	63.06	44.07	70.60
Plastic	34.90	15.97	25.84	12.80
Paper	12.55	15.36	13.78	7.30
Textiles	9.21	4.85	6.43	3.20
Resident	6.32	3.14	4.28	2.40
Wood	0.30	0.19	0.23	0.10
Metals	4.61	0.15	2.50	0.30
Rubber	0.00	0.02	0.01	0.20
Soil	0.00	0.45	0.17	0.10
Glass	4.61	0.63	2.71	3.00

Table 3 The classification process of the waste sector

Phases		Implementation
Pilot project	1995	Establish pilot of garbage classification in No. 5 Caoyang village
	1998	Special recycling of used batteries and used glass
Promotion stage	1999	Garbage classification incorporated into environmental plan
		Issue files of living waste classification collection and disposal
	2000	Establish pilots of garbage classification in 100 residential areas
		One of the eight pilot cities of garbage classification in China
	2002	Focus on promoting the work of classification in incineration area
	2006	Coverage ratio of garbage classification is more than 60% in urban areas
	2007	Promoting the new style: four categories, five categories
	2009	Coverage ratio of garbage classification is 100% around Expo park
	2010	Coverage ratio of garbage classification is more than 70% in urban areas
Adjustment stage	2011	Overfulfilled pilots of classification in 1,009 residential areas
		Realize target of 5% reduction rate per capita in 2010, 0.76 kg/day
	2012	Establish 3,271 new pilot sites
		Realize target of 5% reduction rate of per capita in 2010, 0.74 kg/day
	2013	Increased classification pilot: 2016, coverage area: 8×10^5households
		Realize target of 5% reduction rate per capita in 2010, 0.7 kg/day
	2014	Classification pilot: 11,000, coverage area: 2.8×10^6 households
		Realize target of 5% reduction rate per capita in 2010, 0.66 kg/day

main contributors, with values of 57.28, 24.21, and 0.34 CO_2-eq, since some biocarbon in landfills is converted as CH_4, while that in incineration plant will be as CO_2, which will not be considered as the source for GW impact [3].

On the other hand, the source separation program has been encouraged and implemented in Shanghai to reduce the amount of MSW generation. The history of the classification program in Shanghai was summarized in Table 3.

With the implementation of source separation, we can conclude that the waste disposal amounts and the relative GHG emissions could be reduced significantly. Usually, the GHG emission from incineration plant will be lower than that from landfill per MSW disposal, even so, CO_2 capture and storage could be the promising mitigation methods for the incineration plant based on the high content of 8–12% CO_2 content in flue gas [3].

4.3 Mitigation Technologies for Landfills

Once the MSW was disposed of, especially in landfills, the typical GHG mitigation processes, such as soil cover, landfill gas (LFG) collection and flaring, LFG collection and electricity production, and LFG collection and purified/utilization, could be applied for CH_4 mitigation [2, 6]. The mitigation technologies should be implemented according to the local conditions. A major control of CH_4 emissions can be done by limiting the amount of organic matter at the source through the introduction of RL and MBT processes. For the western inland regions, CH_4 mitigation processes such as LCF, FSC, and LCP should be the first choice, whereas in the eastern coastal regions, the waste diversion options are the most promising measures.

Landfill gas collection/flaring and CH_4 oxidation through soil cover have been proven to be cost-effective and practical mitigation measurements [2, 14]. For the former one, it has been widely applied in many large- and middle-scale landfills with the incentives of CDM projects, especially the power generation from biogas. On-site methane reduction is the most cost-effective measure for the reduction of CH_4 emissions, and the detailed introduction is shown in part 5 of case study.

5 Case Study: CH_4 Mitigation Through the Improvement of Methanotrophs in Landfill Cover

Landfill soil cover is the forced construction part of a modern sanitary landfill, and it has been proven to be one of the cost-effective CH_4 mitigation technologies that could be applied to all of the landfills. As early as 1970, Whittenbury found that methanotrophs *Methylocystis sporium*, *Methylocystis methanica*, and *Methylocystis albus* showed enhanced growth on methane when malate, acetate, or succinate was also present in the culture medium, and these findings suggested that facultative methanotrophs may exist [15, 16]. Efforts to identify novel methanotrophs didn't significantly regain momentum until the discovery of the *Methylocella palustris* [17], which was a new genus and species within *Alphaproteobacteria* in 1998. After that, *Methylocella silvestris* and *Methylocella tundrae* [18–20] were isolated. These methanotrophs were later shown to be facultative, as they could utilize not only one

Table 4 Facultative methanotrophs

Strains	Discoverer	Discovery time	Discovery area	Metabolic characteristics
Gram-negative, strictly aerobic methane-utilizing bacteria	[23]	In 1970	–	A wide variety of methanotrophs, *sporium, methanica*, and *albus* experienced enhanced growth from methane when malate, acetate, or succinate was also present in the culture medium
Methylobacterium organophilum	[24]	In 1974–1976	Freshwater lake sediments and water	These could utilize a wide range of multicarbon compounds as growth substrates, including many organic acids and sugars. This strain, however, lost the ability to oxidize methane when grown repeatedly on glucose, and other workers subsequently did not succeed in growing the strain on methane [15, 16]
Methylobacterium ethanolicum strain R6	[25–27]	In 1978	An oil refinery in the northeastern United States	These strains were able to grow solely on glucose, but not with other sugars such as fructose, galactose, or sucrose
Methylobacterium ethanolicum	[24, 28]	In 1980	Freshwater lake sediments	They were able to utilize not only methane but also casamino acids, nutrient agar, and a variety of organic acids and sugars for carbon and energy
Methylobacterium hypolimneticum				
Methylomonas sp. strain 761M/761H	[26]	In 1984	A rice paddy in South China	Only 761M could grow on methane, but 761H could not grow on glucose as the sole carbon source, and glucose, as well as acetate and malate, was reported to enhance its growth on methane

(continued)

Table 4 (continued)

Strains	Discoverer	Discovery time	Discovery area	Metabolic characteristics
Methylocella palustris	[17]	In 1998	*Sphagnum* peat bogs	It was the first characterized acidophilic methanotroph which brought significantly regained momentum to identify novel methanotrophs
Methylocella silvestris BL2	[19]	In 2003	Cambisol under a beech-dominated forest stand near Marburg, Germany	These methanotrophs, however, were later shown to be facultative, as they could utilize not only C1compounds for growth but also acetate, pyruvate, succinate, malate and ethanol
Methylocella tundrae	[29]	In 2004	Acidic *Sphagnum* tundra peatlands	
Methylocapsa aurea	[21]	In 2010	A soil sample collected in March 2003 from under a small ephemeral brook in a forest near Marburg, Germany	It was identified that they could utilize acetate as the sole growth substrate; however, *M. aurea* only expresses pMMO
Methylocystis strain H2s/*heyeri* H2	[22]	In 2011	A sample collected in July 2001 from 10 cm below the surface of *Sphagnum* peat	It possesses both forms of methane monooxygenase (particulate and soluble MMO) and a well-developed system of intracytoplasmic membranes (ICM) and is able to grow with the acetate absence of methane
Methylocystis strain SB2	[22]	In 2011	A spring bog in southeastern Michigan	It was able to utilize methane, ethanol, or acetate as growth and can only express pMMO substrates

(continued)

Table 4 (continued)

Strains	Discoverer	Discovery time	Discovery area	Metabolic characteristics
Methylocystis strain H2sT *Methylocystis* strain S284	[30]	In 2012	An acidic (pH 4.3) *Sphagnum* peat bog lake (Teufelssee, Germany) and an acidic (pH 3.8) peat bog (European north Russia)	They possess both a soluble and a particulate methane monooxygenase. The preferred growth substrates are methane and methanol. In the absence of C1 substrates, however, these methanotrophs a22re capable of slow growth on acetate

carbon compound for growth but also acetate, pyruvate, succinate, malate, and ethanol.

Shortly thereafter, *Methylocapsa* [21] and *Methylocystis* [22] were also isolated and suggested to be facultative methanotrophs. In contrast to *M. silvestris*, the newly acidophilic methanotroph, *Methylocapsa aurea*, only expresses pMMO and has well-developed intracytoplasmic membrane (ICM) systems. Additionally, *M. aurea* grew best on methane, with a maximum $OD_{600} = 1.2$ $\mu_{max} = 0.018\ h^{-1}$. The discovery process of facultative methanotrophs is shown in Table 4.

According to the reported of facultative methanotrophs, *Methylocella silvestris* (BL2) was capable of growth at pH values between 4.5 and 7 (with an optimum at pH 5.5) [19], *Methylocella tundrae* was capable of growth between pH 4.2 and 7.5 (optimum 5.5–6.0) [29], *Methylocapsa aurea* KYG^T grew at pH 5.2–7.2, and *Methylocystis* H2s was mesophilic with optimum pH 6.0–6.5. The optimum pH of *Methylocystis heyeri* H2 [21] and *Methylocystis* SB2 [31] were 5.8–6.2 and 6.8, respectively. *Methylocystis* strain H2sT and S284 grew at pH 5.2–7.2 and 6.0–6.5 [30]. These results indicated that facultative methanotrophs grew well in acidic conditions, and the optimum pH was 5.5–6.5, as shown in Fig. 5.

The relationship between CH_4 oxidation and CH_4 concentration (10–60%) was shown in Fig. 6. It was obvious that there was a positive correlation between the CH_4 oxidation rate and the concentration by providing abundant O_2 in the range of 5.10–32.40 mol day^{-1} m^{-2}. The maximum rate (32.40 mol day^{-1} m^{-2}) of CH_4 oxidation was higher than reported (18.13 mol day^{-1} m^{-2}), suggesting that excess substrate can strengthen the microbial activity of landfill cover soil. The relationship between the CH_4 oxidation rate and the ratio of CH_4/O_2 is shown in Fig. 7. As the ratio of CH_4/O_2 increased (from 0.3 to 1.0), the CH_4 oxidation rate showed dramatic improvement and then decreased rapidly with the ratio of CH_4/O_2 increasing from 1.2 to 1.6. There was a relatively narrow optimal region for the high CH_4 oxidation rate [32–35]. When the CH_4 concentration was less than 20%, CH_4 could be removed completely and then the CH_4 oxidation percentage decreased [35, 36].

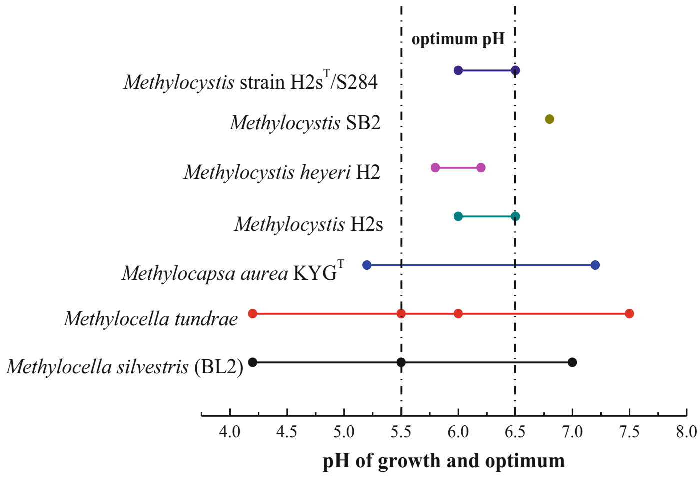

Fig. 5 Growth and optimum pH of facultative methanotrophs

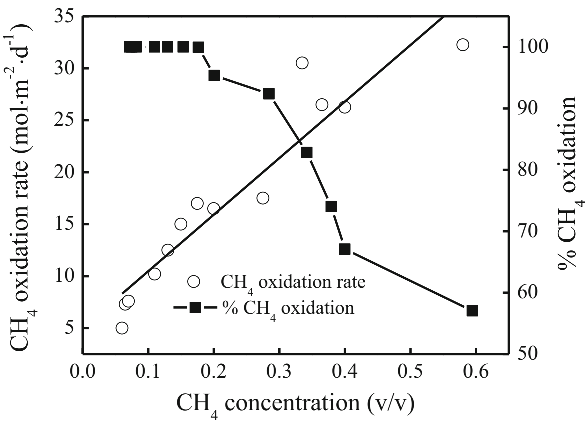

Fig. 6 CH_4 Oxidation rate and CH_4 oxidation percentage change with CH_4 concentration

CH_4 upward diffusion and air downward diffusion were regarded as the limiting factors for biological CH_4 oxidation [37], and 0.2–125 mol m^{-2} day^{-1} CH_4 was fluxed upward and ambient air diffused downward [38]. Accordingly, the vertical distribution patterns of CH_4, O_2, and CO_2 were recorded and shown in Fig. 8. CH_4 content increased with the depth, whereas O_2 content decreased. Unlike CH_4 and O_2, there was an obvious gradient in the distribution of CO_2 that the highest concentration of CO_2 occurred at the 20 cm depths, and the lowest concentration of CO_2 occurred at the surface.

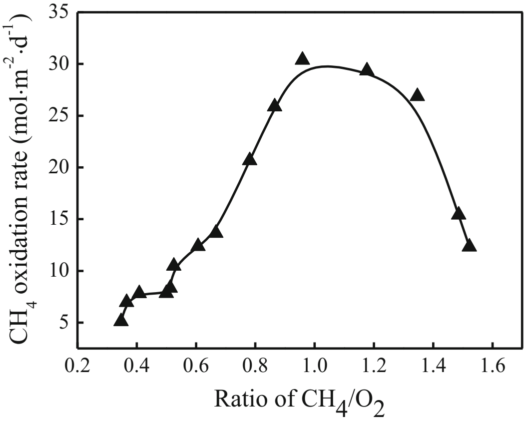

Fig. 7 Oxidation rate of CH_4 change with a ratio of CH_4/O_2

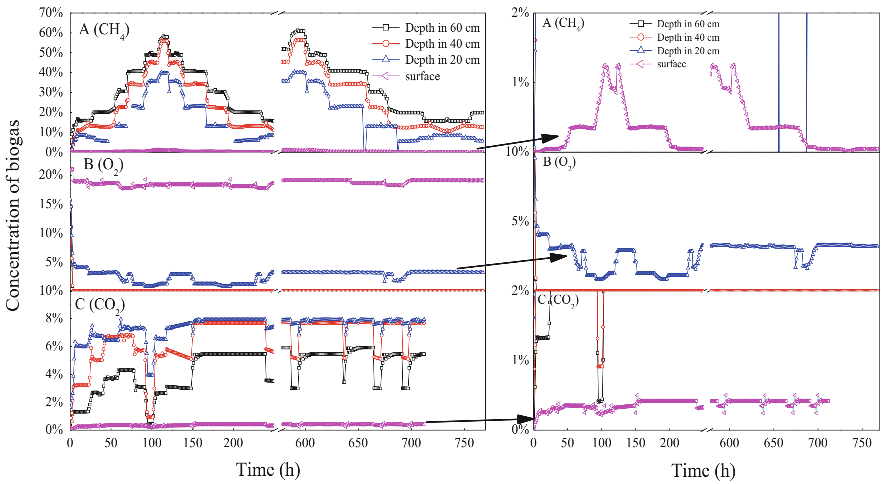

Fig. 8 Real-time monitoring of biogas at different depths of simulated landfill cover soil

The CH_4 concentration varied at the 20 cm (1.4–45.4%), 40 cm (6.0–54.7%) and 60 cm (14.0–57.9%) depths and increased with the increasing of the CH_4 flux (0.2–125 mol m^{-2} day^{-1}).

6 Conclusions

MSW is an important contributor for anthropogenic GHG emissions, and the tendency of GHG emissions was estimated. Around 72.4 million tons of $CO_{2\text{-eq}}$ emissions were released from the waste sector in China in 2013, while those in 1991 amounted to 10.95 million tons. Landfill predominated the GHG emissions, which increased to the peak of 82% (1999) and finally to 69.5% (2013). The GHG division in seven regions was calculated for the interval of 5 years, as waste disposal facilities increased markedly after 2003. The EC was the dominant region, while the occupied percentage decreased greatly from 39.6% (2003) to 26.4% (2013). The NW had a tremendous increase in CO_2 emissions due to the increase in MSW landfilling from 35.9 to 98.5%. Based on the bottom-up calculation method, around 1.48 Mt CH_4 might be released from the 1955 landfills in 2012, 24.88% higher than in 2007. The geographic distribution of CH_4 emissions changed with the mitigation measures' implementation and the improvement in local conditions. More efforts should be emphasized for CH_4 abatement in landfills, and the landfill managers should differentiate among CH_4 mitigation measures for landfills. To reduce CO_2 emissions, the implementation of "PAYT" and the environmental protection tax might be two potential ways to drive the source reduction of MSW generation. The application of the MSW sorting system by the trammel screener at a 40 mm mesh size is the promising pretreatment method for GHG emissions reduction for an incineration plant. CH_4 oxidation through landfill soil cover is one of the promising ways for landfills. The changing of methanotroph activity led to the gradient of the CH_4 oxidation rate in landfill cover. The dominant microorganisms at the phylum level were *Proteobacteria* and *Bacteroidetes*, and the dominant methanotrophs were *Methylobacter*, *Methylococcales*, and *Methylocystis* after CH_4 incubation.

References

1. National Bureau of Statistics of China (NBSC) (2015) China urban construction statistical yearbook (1979–2015). China Plans Press, Beijing (in Chinese)
2. USEPA (2013) Global mitigation of non-CO2 greenhouse gases 2010-2030, EPA-430-R-13-011, United States Environmental Protection Agency Office of Atmospheric Programs (6207J) Washington, DC, 2005. https://www3.epa.gov/climatechange/Downloads/EPAactivities/MAC_Report_2013-Front_Cover.pdf
3. Lou Z, Bernd B, Zhu N, Chai X, Li B, Zhao Y (2015) Environmental impacts of a large-scale incinerator with the mixed MSW of high water content from a LCA perspective. J Environ Sci 30:173–179
4. Ministry of housing and urban-rural development of PRC (MHDC) (2012) The grading lists of sanitary level assessment on MSW landfills and incineration plants. http://std.solidwaste.com.cn/upfile/2013/04/78_1364967479.pdf (in Chinese)
5. Ministry of housing and urban-rural development of PRC (MHDC) (2009) The report on the 2nd national waste treatment facilities sanitary level assessment project. Technol Municip Solid Waste Treat (4):4–7 (in Chinese)

6. Cai B, Liu J, Zeng X, Cao D, Liu L, Zhou Y, Zhang Z (2014) Estimation of CH4 emission from landfill in China based on point emission sources. Adv Climate Change Res 5(2):81–91
7. Zhao Y, Wang L (2003) Conversion of organic carbon on the decomposable organic wastes in anaerobic lysimeters under different temperatures. J Environ Sci 15(3):315–322
8. Zhao Y, Wang L, Huang R, Xu D, Gu G (2002) A comparison of refuse attenuation in laboratory and field scale lysimeters. Waste Manag 22:29–35
9. Lou Z, Cai B, Zhu N, Zhaob Y, Geng Y, Yua B, Chen W (2017) Greenhouse gas emission inventories from waste sector in China during 1949–2013 and its mitigation potential. J Clean Prod 157:118–124
10. Bernd B (2008) Pay-as-you-throw – a tool for urban waste management. Waste Manag 28(12): 2759
11. Vogt R, Derreza-Greeven C, Giegrich J Dehoust G, Möck A, Merz C (2015) The climate change mitigation potential of the waste sector, published by the Federal Environmental Agency of Germany
12. Hussain F, Chaudhry MN, Batool SA (2014) Assessment of key parameters in municipal solid waste management: a prerequisite for sustainability. Int J Sustain Dev World Ecol 21(6): 519–525
13. Zheng L, Song J, Li C, Gao Y, Geng P, Qu B, Lin L (2014) Preferential policies promote municipal solid waste (MSW) to energy in China: current status and prospects. Renew Sust Energ Rev 36:135–148
14. Lou Z, Wang L, Zhao Y (2011) Consuming un-captured methane from landfill using aged refuse bio-cover. Bioresour Technol 102(3):2328–2332
15. Green P, Bousfield I (1983) Emendation of Methylobacterium Patt, Cole, and Hanson 1976; Methylobacterium rhodinum (Heumann 1962) comb. Nov. corrig.; Methylobacterium radiotolerans (Ito and Iizuka 1971) comb. Nov. corrig.; and Methylobacterium mesophilicum (Austin and Goodfellow 1979) comb. Nov. Int J Syst Bacteriol 33:875–877
16. Urakami T, Araki H, Suzuki K-I, Komagata K (1993) Further studies of the genus Methylobacterium and description of Methylobacterium aminovorans sp. nov. Int J Syst Bacteriol 43:504–513
17. Dedysh SN (1998) Isolation of acidophilic methane-oxidizing bacteria from northern peat wetlands. Science 282:281–284
18. Dedysh SN, Knief C, Dunfield PF (2005) Methylocella species are facultatively methanotrophic. J Bacteriol 187:4665–4670
19. Dunfield PF (2003) Methylocella silvestris sp. nov., a novel methanotroph isolated from an acidic forest cambisol. Int J Syst Evol Microbiol 53:1231–1239
20. Im J, Semrau JD (2011) Pollutant degradation by a Methylocystis strain SB2 grown on ethanol: bioremediation via facultative methanotrophy. FEMS Microbiol Lett 318:137–142
21. Dunfield PF, Belova SE, Vorob'ev AV, Cornish SL, Dedysh SN (2010) Methylocapsa aurea sp. nov., a facultative methanotroph possessing a particulate methane monooxygenase, and emended description of the genus Methylocapsa. Int J Syst Evol Microbiol 60:2659–2664
22. Belova SE, Baani M, Suzina NE, Bodelier PL, Liesack W, Dedysh SN (2011) Acetate utilization as a survival strategy of peat-inhabiting Methylocystis spp. Environ Microbiol Rep 3: 36–46
23. Whittenbury R, Phillips K, Wilkinson J (1970) Enrichment, isolation and some properties of methane-utilizing bacteria. J Gen Microbiol 61:205–218
24. Semrau JD, DiSpirito AA, Vuilleumier S (2011) Facultative methanotrophy: false leads, true results, and suggestions for future research. FEMS Microbiol Lett 323:1–12
25. Patel RN, Hou CT, Felix A (1978) Microbial oxidation of methane and methanol: crystallization of methanol dehydrogenase and properties of holo-and apo-methanol dehydrogenase from Methylomonas methanica. J Bacteriol 133:641–649
26. Zhao S-J, Hanson R (1984) Isolate 761M: a new type I methanotroph that possesses a complete tricarboxylic acid cycle. Appl Environ Microbiol 48:1237–1242

27. Zhao S-J, Hanson R (1984) Variants of the obligate methanotroph isolate 761M capable of growth on glucose in the absence of methane. Appl Environ Microbiol 48:807–812
28. Lynch MJ, Wopat AE, O'Connor ML (1980) Characterization of two new facultative methanotrophs. Appl Environ Microbiol 40:400–407
29. Dedysh SN (2004) Methylocella tundrae sp. nov., a novel methanotrophic bacterium from acidic tundra peatlands. Int J Syst Evol Microbiol 54:151–156
30. Belova SE, Kulichevskaya IS, Bodelier PL, Dedysh SN (2013) Methylocystis bryophila sp. nov., a facultatively methanotrophic bacterium from acidic Sphagnum peat, and emended description of the genus Methylocystis (ex Whittenbury et al. 1970)Bowman et al. 1993. Int J Syst Evol Microbiol 63:1096–1104
31. Im J, Lee SW, Yoon S, DiSpirito AA, Semrau JD (2011) Characterization of a novel facultative Methylocystis species capable of growth on methane, acetate and ethanol. Environ Microbiol Rep 3:174–181
32. Fei PA, Wang Q (2008) Analysis on the mechanism and influence factors of methane oxidation in landfill soil covers. Renew Energ Resour 97–101
33. Kjeldsen CSAP (2004) Environmental factors influencing attenuation of methane and hydrochlorofluorocarbons in landfill cover soils. J Environ Qual 33:72–79
34. Park JR, Moon S, Ahn YM, Kim JY, Nam K (2005) Determination of environmental factors influencing methane oxidation in a sandy landfill cover soil. Environ Technol 26:93–102
35. Sadasivam BY, Reddy KR (2014) Landfill methane oxidation in soil and bio-based cover systems: a review. Rev Environ Sci Biotechnol 13:79–107
36. Chanton J, Abichou T, Langford C, Spokas K, Hater G, Green R, Goldsmith D, Barlaz MA (2011) Observations on the methane oxidation capacity of landfill soils. Waste Manag 31:914–925
37. Park J-R, Moon S, Ahn YM, Kim JY, Nam K (2005) Determination of environmental factors influencing methane oxidation in a Sandy landfill cover soil. Environ Technol 26:93–102
38. Semrau JD (2011) Current knowledge of microbial community structures in landfills and its cover soils. Appl Microbiol Biotechnol 89:961–969

The Reduction of Greenhouse Gas Emissions Through the Source-Separated Collection of Household Waste in Germany

Christoph Wünsch and Franz-Georg Simon

Abstract The production of secondary materials from waste materials requires, in most cases, significantly lower energy amounts than the primary material production of raw materials. Along with lower energy demand, the greenhouse gas emissions produced are also lower. The duty of a modern waste management system should therefore be to collect and sort the waste materials in a way that the highest amounts of single material fractions with the highest qualities can be generated. In this contribution, the greenhouse gas balances of the theoretical treatment of the household waste, if collected as mixed waste in sanitary landfills, in waste incineration plants, or in mechanical-biological treatment plants, are compared to the existing separate waste collection and treatment in Germany in 2014. The results show that the treatment of the mixed collected household waste in sanitary landfills would lead to a significant release of greenhouse gases. The treatment in MBTs with the recovery of valuables and the further disposal of the biologically stabilized fraction on landfills, as well as the treatment of the high calorific fraction (also called refuse derived fuel – RDF) in RDF plants, coal-fired power plants, or cement kilns, would lead to small amounts of avoided greenhouse gas emissions. The thermal treatment in waste incineration plants would lead to moderate amounts of avoided greenhouse gases. Only with the actually practiced separate collection and treatment of household waste were significant amounts of greenhouse gas emissions avoided. In total, this is approximately 5.5 million tons of carbon dioxide equivalents for approximately 45.5 million tons of separate collected and treated household waste in Germany in 2014.

C. Wünsch (✉)
Institute of Waste Management and Circular Economy, Technische Universität Dresden, Pirna, Germany
e-mail: christoph.wuensch@tu-dresden.de

F.-G. Simon
Bundesanstalt für Materialforschung und -prüfung, Berlin, Germany

R. Maletz et al. (eds.), *Source Separation and Recycling*,
Hdb Env Chem (2018) 63: 269–288, DOI 10.1007/698_2017_35,
© Springer International Publishing AG 2017, Published online: 25 May 2017

Keywords Greenhouse gas accounting, Greenhouse gas mitigation, Household waste, Material recycling, Separate collection

Contents

1 Cumulative Energy Demand and Global Warming Potential

The production of materials for the final manufacturing of goods needs energy, and this energy is usually connected to the release of greenhouse gas (GHG) emissions. The more extensive the treatment processes are, the more energy is used, and the higher the global warming potential (GWP) of a material is.

1.1 Cumulative Energy Demand and Global Warming Potential of Primary Material Production

Primary materials like metals are usually produced from ores and are processed in several treatment steps. Different kinds of plastics are usually produced from crude oil, paper from wood, and glass from different raw materials. Along the process chain of the materials, energy is used for the excavation of raw materials, their transport, their processing, and their final production. Figure 1 shows the cumulative energy demand (CED) [4] and the respective global warming potential (GWP) of the primary production of different materials.

The production chain of aluminum (the excavation of bauxite, the crushing and grinding of the bauxite, the production of aluminum oxide from the intermediate hydroxide, and the final production of aluminum by melt flow electrolysis) is very energy intensive, especially in units of primary energy because of the electricity consumption for the reduction of the oxide [5]. For the production of one ton of aluminum, almost 176 MJ of energy are used. This high energy consumption leads to a release of high amounts of greenhouse gas emissions of almost 17 tons of CO_2 equivalents per ton (Mg $CO_{2,eq}$/Mg) of aluminum [1]. CED and the corresponding GWPs for other industrial metals, such as copper and especially for steel, are lower because for the chemical reduction, no electricity is used. Copper has a CED of approx. 70 MJ, and the production of one ton has a GWP of approx. 6 Mg of $CO_{2,eq}$. The reducing agent, at least for sulfidic ores, is sulfur. For steel (reduction of iron ore is performed with coke), these numbers are with approx. 23 MJ/Mg and less than 2 Mg $CO_{2,eq}$/Mg of steel even lower. The CED of most bulk plastics is in the range of copper, around 70 MJ/ton. But the GWP of the plastics production is in the range of steel between approx. 1 and 3 Mg of $CO_{2,eq}$/Mg [6]. Paper and especially glass have a low CED of approx. 41 and approx. 17 MJ/Mg, respectively. The GWP of their production with approx. 1 Mg of $CO_{2,eq}$/Mg is also comparatively low [2].

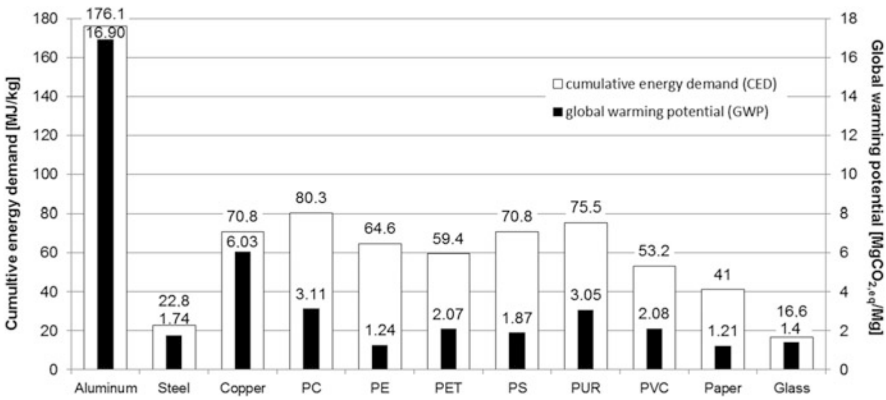

Fig. 1 Cumulative energy demand and global warming potential of primary material production [1–4]

1.2 Global Warming Potential of Primary and Secondary Material Production and Greenhouse Gas Emissions Avoided by Material Recycling

The recovery and the recycling of waste materials and the production of secondary materials have a much lower CED than primary material production. Usually, the waste materials just have to be sorted, cleaned from other fractions, and finally treated (e.g., melted for metals, glass, and most plastics). This leads to a much lower GWP for the secondary material production. A comparison of the GWP between the primary and secondary material production is illustrated in Fig. 2.

The savings of greenhouse gas emissions by secondary material production are particularly high for metals. The production of secondary aluminum (1.7 Mg of $CO_{2,eq}$/Mg) releases just 10% of the GHG emissions versus the primary production (16.9 Mg of $CO_{2,eq}$/Mg). Accordingly, 95% of greenhouse gas emissions can be avoided. For steel and copper, the reduction potential is approx. 35%, for most plastics around 50%, and for paper and glass at least 20%. Figure 3 shows the amount of GHG emissions that can be avoided by the production of secondary materials.

Especially the production of secondary aluminum, with approx. 15 Mg of $CO_{2,eq}$/Mg and copper with approx. 4 Mg of $CO_{2,eq}$/Mg, has very high GHG reduction potential. But also the production of steel and plastics has reduction potential of approx. 1 Mg of $CO_{2,eq}$/Mg for secondary material.

Based on these numbers, it should be the duty of waste management to collect and sort the waste materials to generate the highest amounts of single material fractions with the highest qualities.

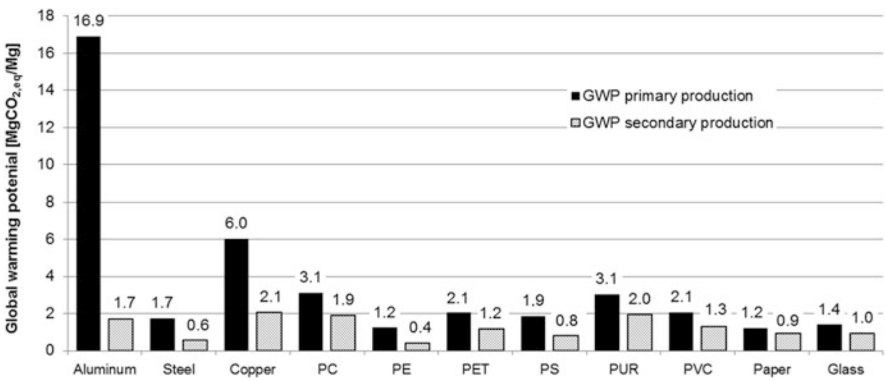

Fig. 2 Global warming potential of primary and secondary material production [1–3, 6]

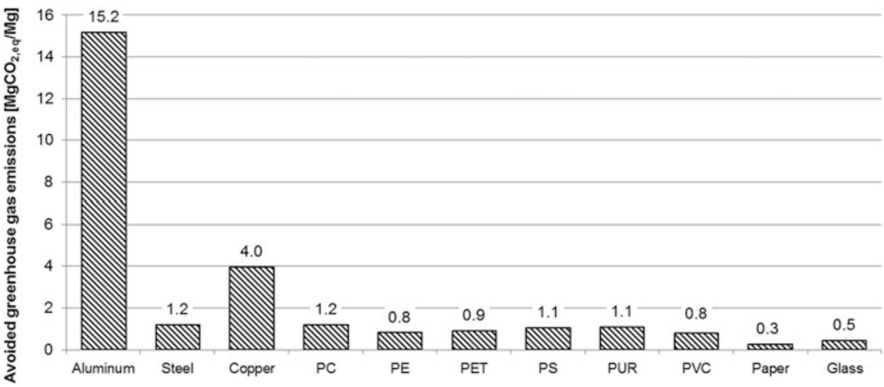

Fig. 3 Greenhouse gas emissions avoided by the production of secondary materials

2 Greenhouse Gas Accounting

The accounting of GHGs is always based on many pieces of data and several assumptions. GHG accounting in the waste management sector in particular, with its different treatment and processing options, is not trivial. On the one hand, the treatment of the waste generates GHG emissions in the consumption (electrical power and heat) of the treatment plants, as well as from different degradation and oxidation processes. On the other hand, the production of power and heat and the recovery of secondary materials from waste treatment processes avoid GHG emissions.

The amount of released and avoided GHG emissions heavily depends on:

- Treated waste type
- Composition of waste type
- Amount of renewable (biogenic) and nonrenewable (fossil) carbon
- Energy consumption/efficiency of the treatment facilities
- Substitution scenarios (e.g., energy mix that is used)
- Substitution factors for the recovery of secondary materials
- Accounting of only climate-relevant or also climate-neutral emissions
- Accounting of only CO_2 or also CH_4 and N_2O

The following calculations are based on German conditions (waste composition, energy mix, efficiency of German waste treatment plants, ...) with the accounting of only climate-relevant GHG emissions and of CO_2, CH_4, and N_2O. Climate-relevant emissions are those emissions that lead to an increase of GHG emissions in the atmosphere. All CH_4 and N_2O emissions belong to these emissions, as well as all emissions that are generated by the thermal oxidation of fossil-fixed carbon, like in plastics. All CO_2 emissions that are released by biological degradation processes or thermal oxidation of carbon fixed in organic matter (plastics excluded) are by definition climate neutral.

3 Treatment of Mixed Municipal Solid Waste

Household waste can be either collected as mixed waste and treated/disposed of in landfills, waste incineration plants, or sorting plants like mechanical (biological) treatment plants or separately collected and treated. Figure 4 compares the mixed and source-separated waste collection and waste treatment regarding the effort in collecting and separating the waste, as well of the amounts and qualities of recovered secondary materials and residues.

The collection of source-separated household waste involves a higher effort regarding collection (more bins, more and different collection vehicles, more collection logistics), but because of the higher homogeneity of the collected waste, it requires a lower effort in post-sorting the different waste types. Finally, higher amounts of materials in higher qualities can be separated, and lower amounts of residues have to be disposed of.

The waste collection occupies a large part of the cost of waste management but has a negligible effect on the greenhouse gas emissions released compared to the treatment/disposal of the waste. Thorneloe calculated that the United States released GHG emissions of 0.5 and 1 million Mg of CO_2 equivalents for the collection and transportation of 116 million tons of municipal solid waste (MSW) in 1974 and 197 million tons of MSW in 1997 [7]. That makes approx. 50 kg of $CO_{2,eq}$/Mg MSW. The amount of transported waste for the collection of mixed or source-separated waste remains the same, though more and maybe smaller vehicles have to be used for the transport of source-segregated wastes.

A rough calculation shown in Table 1 shows that the GHG emissions that have to be accounted for the production of the trucks are very small, and with the release of GHG emissions of approx. 30 kg of $CO_{2,eq}$/Mg MSW for the transportation, a suitable result of approx. 33 kg of $CO_{2,eq}$/Mg of collected MSW can be assumed.

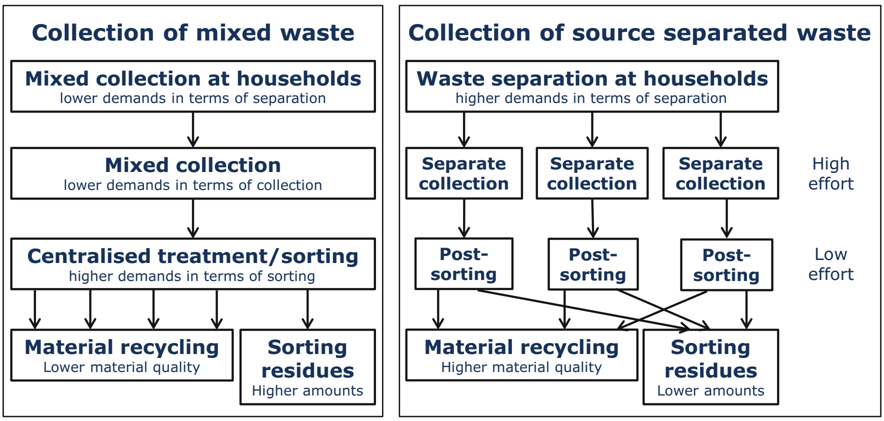

Fig. 4 Comparison of mixed and source-separated waste collection

Table 1 Calculation of GHG emissions released by truck production and fuel consumption

GHG emissions by fuel consumption		GHG emissions from truck production	
Fuel consumption truck	50 L/100 km	CO_2 equivalent truck production	14 Mg $CO_{2,eq}$/Mg truck
Average transport distance	100 km	Average weight of a truck	10 Mg
CO_2 equivalent diesel	2.94 kg $CO_{2,eq}$/L	CO_2 equivalent truck	140 Mg $CO_{2,eq}$/truck produced
Average amount of waste on truck	5 Mg	Average number of km for a truck	500,000 km
CO_2 equivalent/Mg waste	29.4 $O_{2,eq}$/Mg waste	CO_2 equivalent/Mg waste	2.8 kg $CO_{2,eq}$/Mg waste

3.1 Landfill

If German MSW would be collected as mixed waste and disposed of on sanitary landfills, most of the biodegradable material would be degraded under anaerobic conditions, and the carbon would be transferred to CO_2 and CH_4. The carbon fixed in biogenic material and not degraded by microorganisms is stored (carbon sequestration) in the landfill. It is assumed that 70% of the carbon in biogenic materials is degraded and 30% is sequestrated in the landfill. Further parameters used for the calculation are:

- Organic carbon in the wet MSW: 142 kg/Mg wet waste (ww)
- Methane correction factor (MCF): 0.95
- Fraction of methane by volume (F): 0.55
- Methane recovery rate (R): 0.6
- Oxidation factor (OX): 0.1
- Electrical net efficiency power unit: 35%
- Thermal net efficiency power unit: 10
- Methane slip power unit in vol.% CH_4: 0.5%

Figure 5 shows the release of more than 500 kg of CO_2 equivalents per ton of landfilled mixed MSW in the form of methane. In the generation of electricity, fossil fuels out of the electricity mix of Germany would be substituted, and 120 kg of $CO_{2,eq}$/Mg MSW would be avoided. Together with 12 kg of $CO_{2,eq}$/Mg MSW for the delivery of district heat and 156 kg of $CO_{2,eq}$/Mg MSW for sequestrated carbon, total GHG net emissions of 239 of $CO_{2,eq}$/Mg MSW are calculated.

It should be pointed out that the disposal on an open dump would generate net GHG emissions of 1,153 kg of $CO_{2,eq}$/Mg MSW.

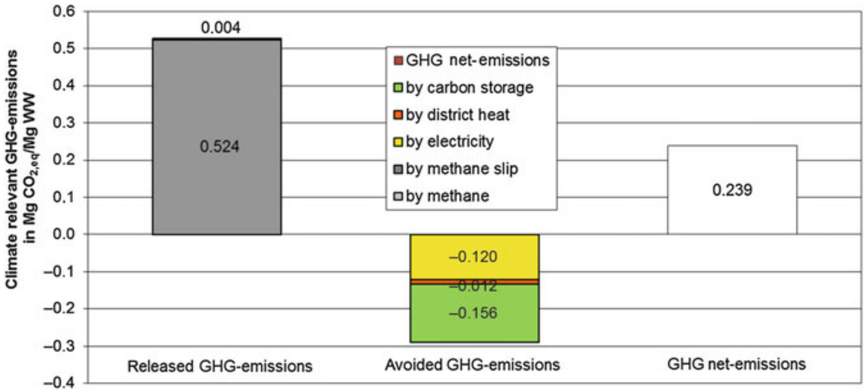

Fig. 5 GHG balance for the disposal of mixed collected MSW on sanitary landfills

3.2 Mechanical-Biological Treatment

The aim of the mechanical-biological waste treatment (MBT) is to recover some valuable materials and to split the rest into a high caloric and a low calorific fraction. The low calorific fraction is further biologically stabilized and finally landfilled, and the high calorific fraction (also called refuse-derived fuel – RDF) thermally utilized in RDF plants, coal-fired power plants, or cement kilns.

In modern MBT plants, approx. 80% of the ferrous and approx. 50% of the nonferrous metals can be recovered. Beside metals, sometimes valuable plastics like PET or glass are also recovered. If the low calorific material is anaerobically treated, some biogas can be produced and thermally used. In German MBTs, 59% of the input can be recovered as RDF, 13% is finally landfilled, and 2.4% is recovered as other recyclables (plastics, glass, wood, biowaste) and 2.3% as metals. One percent of the material can be converted to biogas. Thirteen percent is converted into CO_2 and H_2O during the aerobic treatment of the low calorific fraction, and the final seven percent is further treated in other treatment plants [8]. Based on the data from Ketelsen and Kanning [8], 55% of the RDF produced is finally treated in RDF-fired power plants with net efficiencies of 18.5% electrical power and 20.5% thermal [9], 17% in waste incineration plants with net efficiencies of 11.8% electrical and 31% thermal [10], 10% in coal-fired power plants with net efficiencies of 36.3% electrical and 1.6% thermal [11], and 12% in cement kilns where the fuel mix of the cement kilns [12] is substituted.

Figure 6 shows the release of some minor amounts of GHG emissions from MBT plants, some higher amounts from the degradation of the stabilized low calorific fraction on the landfill, and the highest amount from the incineration of the produced RDF. In total, 434 kg of $CO_{2,eq}$/Mg-treated MSW would be released. Through the production of biogas and the generation of energy in the MBTs, and from the generation of energy out of the landfill gas, some minor amounts of GHG emissions would be avoided. The highest amount of more than 400 kg of $CO_{2,eq}$/Mg

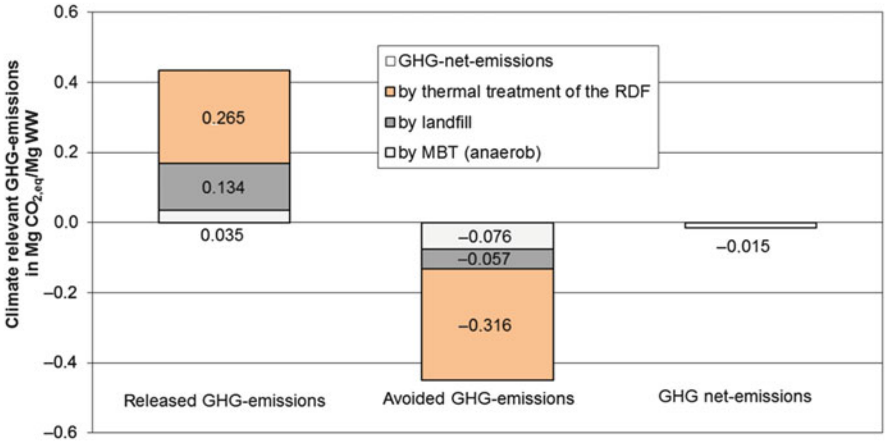

Fig. 6 GHG balance for the treatment of mixed, collected MSW in MBT with the utilization of the produced RDF in RDF plants and the disposal of the stabilized low calorific fraction in sanitary landfills

MSW would be avoided by the generation of electricity and heat out of the high calorific fraction and the substitution of regular fuels in cement kilns.

In total a reduction of GHG, net emissions of 0.015 kg of $CO_{2,eq}$/Mg wet MSW would be the result.

3.3 Waste Incineration

The primary target of waste incineration is the safe and environmentally sound disposal of waste. The second target is the recovery of energy. The incineration of the waste and the oxidation of the fossil-fixed carbon, e.g., in plastics into CO_2, lead to a release of climate-relevant GHG emissions. On the other hand, the generation and delivery of energy in the form of electricity and heat avoids greenhouse gas emissions. Also, the recovery of some metals from the incinerator bottom ash avoids GHGs. The energy efficiency of German waste incineration plants in 2014 was on average approx. 12% electrical for the delivery of electric power and approx. 31% for thermal energy (district heat and steam) [10]. On a European level, the values are similar. In a weighted average, the electrical efficiency is 14.9%, and the efficiency for thermal energy is 34.6% [13]. Figure 7 shows the GHG balance if the mixed, collected MSW would be treated in waste incineration plants.

The emission of CO_2 in the incineration would lead to 324 kg of $CO_{2,eq}$/Mg wet MSW, and the generation of nitrous oxides is negligible. From the generation and delivery of electricity and heat together, 337 kg of $CO_{2,eq}$/Mg wet MSW would be avoided. Additionally, approx. 30 kg of $CO_{2,eq}$/Mg wet MSW would be avoided

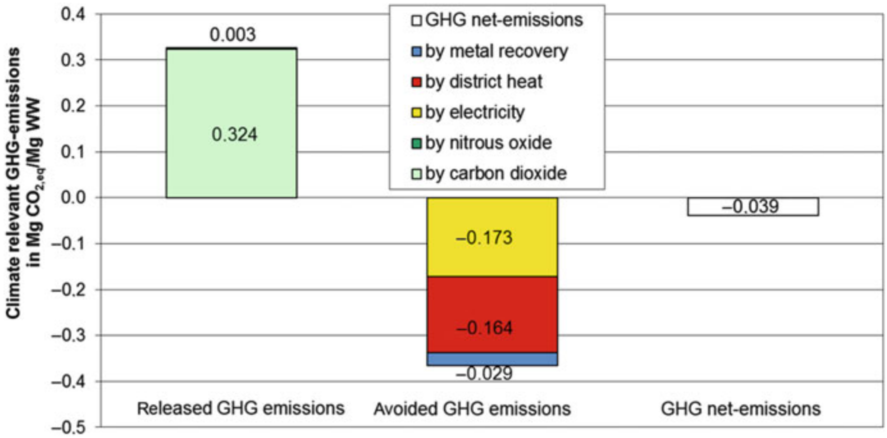

Fig. 7 GHG balance for the treatment of mixed collected MSW in waste incineration plants

through the recovery of metals from the incinerator bottom ash. Because of the relatively low average energy efficiencies of the German waste incineration plants and the therefore relatively small amount of avoided GHG emissions, in total, only a small amount of 39 kg of $CO_{2,eq}$/Mg wet MSW would be avoided from the treatment of the mixed collected MSW in waste incineration plants. Waste incineration plants with exclusive heat production achieve efficiencies of 77.2% [13], resulting in a much higher amount of avoided GHG emissions of 112 kg of $CO_{2,eq}$/ Mg wet MSW.

3.4 *Comparison of Mixed Municipal Solid Waste Treatment Options*

The three technological solutions for treating mixed municipal solid waste perform differently in terms of released greenhouse gases and also in the recovery of secondary materials and energy to avoid greenhouse gases. Figure 8 shows these differences calculated in advance in an overview.

In 2014, approx. 45.5 million Mg of mixed household municipal solid wastes were collected in Germany [14]. If this material would be disposed of on sanitary landfills, almost 11 million Mg of CO_2 equivalents would have been released. The material treated in MBT with the recovery of some valuables, the splitting of the rest into a high caloric and a low calorific fraction where the low calorific fraction would be further biologically stabilized and finally landfilled and the high calorific fraction (RDF) would be further thermally utilized, would avoid, in total, approx. 0.7 million Mg of CO_2 equivalents. The material thermally treated in waste incineration plants would avoid approx. 1.8 million Mg of CO_2 equivalents in total. This comparison already shows that the pretreatment of mixed MSW, either

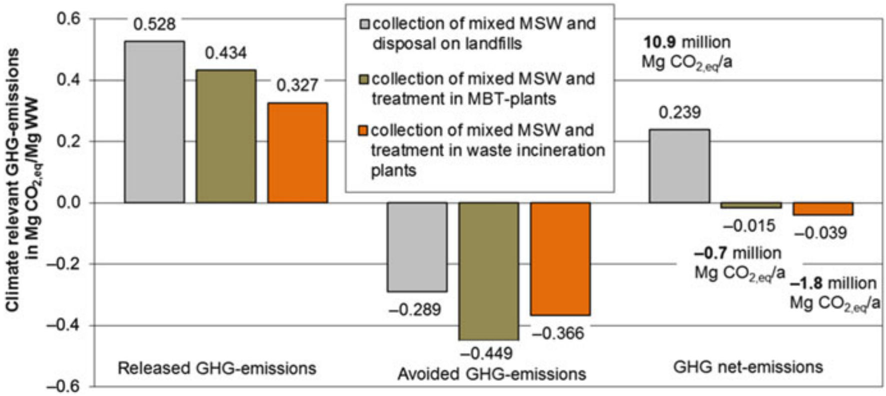

Fig. 8 Comparison of GHG balances for the treatment of mixed, collected MSW in sanitary landfills, MBT-RDF plants, and waste incineration plants

mechanically-biologically and/or thermally, leads to a significant reduction in greenhouse gas emissions from the waste management sector.

With these two more advanced technologies, the energy content of the waste is used to produce electricity and heat and/or substitute regular fuels, but only metals are recovered as secondary resources. As already described in Fig. 3, other materials also, like different plastics, paper, or glass, have high GHG-reduction/ substitution potential. But only with the separate collection of these materials can secondary resources be recovered in high amounts and high qualities to further improve the GHG balance of the waste management sector in Germany.

4 Treatment of Source-Separated Waste Fraction

Source-separated waste is more homogeneous and thereby easier and more efficient to treat. The amount of recovered recyclables/materials and their quality is usually higher than for mixed MSW.

4.1 Limits of Source Separation

Different types of waste can be separately collected directly at households, at container locations, or at recycling centers. For various reasons, people are not always able to sort their waste into the correct waste bin, and often people are too lazy to sort, and valuables end up in the mixed residual waste bin. As a result, false materials can be found in the bins of the different separate collected waste types, which makes proper recycling difficult and lowers the recycling rates. Also, a high

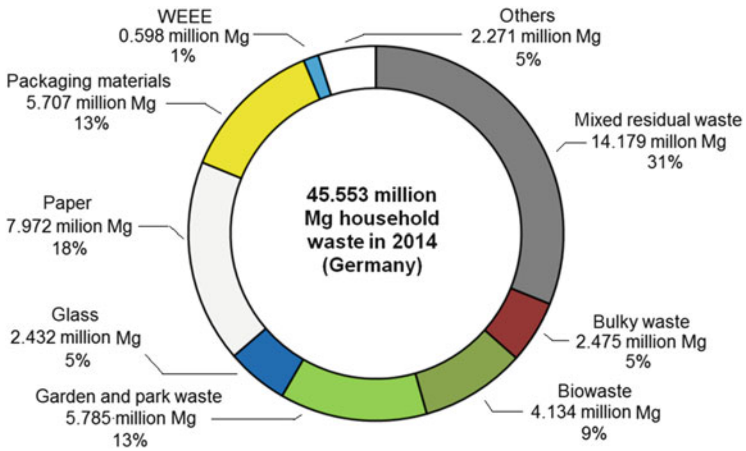

Fig. 9 Separately collected waste types from households in Germany in 2014 (According to [14, 15])

amount of waste is still disposed of in the mixed residual waste bin. Figure 9 shows the distribution of the 45.6 million Mg of household waste in Germany in 2014 in the different separately collected waste types.

Still, more than 30% of the household waste in Germany is collected as mixed residual waste. In the following chapters, the amount of materials that are wrongly disposed of in their respective bins is also described.

4.2 Glass

In Germany in 2014, 2.445 million Mg of glass was collected separately [14]. Almost 100% of this collected glass was mechanically treated to remove false fractions of ceramics, paper and aluminum, as well as tinplate caps. Approx. 10% of the collected glass was false fractions that were removed [15], and approx. 2.2 million Mg were recycled. With the substitution factor of glass with 0.45 Mg of $CO_{2,eq}$/Mg recycled glass, approx. 1 million Mg of CO_2 equivalents were avoided. In addition, approx. 3,100 Mg of aluminum and 8,200 Mg of tinplate were recovered [15]. With recycling losses of approx. 60% for aluminum and approx. 10% for tinplate, finally, approx. 1,200 Mg of aluminum and 7,400 Mg of tinplate were recycled. With the substitution factors of aluminum with 15.18 and for tinplate with 1.19 Mg of $CO_{2,eq}$/Mg additionally, approx. 28,000 Mg of CO_2 equivalents were avoided.

In total, more than 1 million Mg of CO_2 equivalents were avoided in Germany in 2014 through the separate collection and treatment of glass and its impurities.

4.3 Paper

Almost 8 million Mg of waste paper was separately collected in 2014 [14]. Almost 100% was post-sorted in waste paper sorting plants, and only a small amount was thermally treated and composted. Approx. 23% was removed as rejects [15], and approx. 6.1 million Mg were recycled. With the substitution factor of 0.27 Mg of $CO_{2,eq}$/Mg for paper, around 1.65 million Mg of CO_2 equivalents were avoided. The recovered rejects are usually thermally treated, often in in-house thermal treatment plants. Information about the composition of the rejects (containing plastics, cellulose fibers, . . .) and the recovered amount of energies are not available. Thus, it was assumed that the same amount of CO_2 equivalents was avoided through energy production, as it was released by the generation of GHGs through the combustion of the plastics it contained. In addition, a relatively small amount of 66,000 Mg was thermally treated [14]. We assume the treatment in RDF-fired power plants that leads to the avoidance of approx. 45,000 Mg of CO_2 equivalents. Finally, approx. 30,000 Mg of waste paper was composted. We assume that the compost can be used as fertilizer with a substitution factor of 0.01 Mg of $CO_{2,eq}$/Mg [16], leading to an avoidance of just 300 Mg of CO_2 equivalents.

In total, almost 1.7 million Mg of CO_2 equivalents were avoided in 2014 in Germany through the separate collection and treatment of paper.

4.4 Light Packaging Waste

5.7 million Mg of light packaging material was separately collected in Germany in 2014. Almost 0.2 million Mg were directly treated in waste incineration plants, and about 0.8 million Mg were directly thermally treated, primarily in RDF-fired plants [14]. It is assumed that for the treatment of light packaging material for both together, in incineration plants and RDF-fired plants, the amount of released and avoided GHG emissions is balanced. A detailed calculation is impossible because neither the exact composition of the treated material is known nor the amount of electricity and heat that was produced from this material.

The major part of approx. 4.7 million Mg of the collected light packaging material was mechanically treated to recover materials for recycling. In these material recovery facilities (MRF), approx. 1.3 million Mg were recovered as false fractions and treated in waste incineration plants. Again, because of no information about the composition of this material, the GHG balance of this treatment is assumed to be balanced. Table 2 shows the final treated amounts of valuable materials in the form of plastics, tinplate, aluminum, and composites and how much was finally recovered for thermal treatment and material recycling.

As shown in Table 2, because of process losses, only 78% of the plastics, 84% of the tinplate, 35% of the aluminum, and 75% of the composites could be transferred into secondary materials [15]. As a result, approx. 1.6 million Mg/a of the recovered

Table 2 Calculation of material flows for separately collected light packaging waste

Material	Treated in MRF in Mg/a	Recycled in Mg/a	Thermally treated in Mg/a	Material recycling in Mg/a	Purity (%)	Produced secondary material in Mg/a
Plastics	2,438,752	2,426,559	1,208,426	1,218,132	78	944,053
Tinplate	407,342	378,828	26,518	352,310	94	329,410
Aluminum	88,920	81,628	9,714	71,915	35	25,170
Composites	502,554	502,554	366,554	136,000	75	102,000

materials were finally thermally treated, and approx. 1.4 million Mg of secondary materials were produced.

The amount of secondary materials produced multiplied with the respective GHG substitution factors in Fig. 3, leading to avoided GHG emissions of approx. 1.66 million Mg of CO_2 equivalents (for composites, the substitution factor for paper of 0.27 Mg of $CO_{2,eq}$/Mg was used – these recovered composites consist primarily of paper – and an average factor for plastics of 0.91 Mg of $CO_{2,eq}$/Mg). The thermal treatment of plastics and composites in RDF-fired plants is calculated to a GHG balance of approx. 0.4 million Mg of released CO_2 equivalents for plastics and of approx. 0.1 million Mg of avoided CO_2 equivalents for composites.

In total, the separate collection and treatment of packaging materials avoided approx. 1.4 million Mg of CO_2 equivalents in 2014.

4.5 Biowaste

Biowaste includes separately collected biowaste and biodegradable garden and park waste totaling 9.9 million Mg in 2014 [14]. Only small amounts of approx. 0.3 million Mg were thermally treated. We assume the treatment takes place in specific biomass power plants with a calculated GHG substitution factor of 0.309 Mg of $CO_{2,eq}$/Mg. The thermal treatment leads to avoided GHG emissions of approx. 90,000 Mg of CO_2 equivalents.

Approx. 25% (approx. 2.5 million Mg) of the biologically treated biowaste is processed anaerobically in digestion plants and approx. 75% (approx. 7.4 million Mg) decomposed in composting plants. Depending on the quality of the treatment of biowaste in the composting and digestion plants, and depending on the substitution scenario for the produced compost and/or digestate, different GHG emission and substitution factors can be found in the literature. For the German case numbers, around 0.08 Mg of $CO_{2,eq}$/Mg of biowaste for digestion and around 0.01 Mg of $CO_{2,eq}$/Mg for composting is listed in the literature [17, 18]. With these substitution factors avoided, GHG emissions of approx. 0.2 million Mg of CO_2 equivalents can be calculated for the digestion and approx. 75,000 Mg of CO_2 equivalents for the composing.

In total, the separate collection of biowaste (including garden and park waste) avoided approx. 0.36 million Mg of CO_2 equivalents in 2014.

4.6 Bulky Waste

Almost 2.5 million Mg of bulky waste were separately collected in 2014 in Germany. Approx. 0.3 million Mg were directly incinerated in waste incineration plants [14]. With a calculated GHG substitution factor of 0.18 Mg of $CO_{2,eq}$/Mg, approx. 56,000 Mg of GHG emissions were avoided. Approx. 0.8 million Mg were thermally treated. We assume the thermal treatment took place in specific biomass power plants or in RDF-fired plants with a calculated GHG substitution factor of 0.586 Mg of $CO_{2,eq}$/Mg. This leads to an avoidance of GHG emissions of approx. 0.5 million Mg of CO_2 equivalents. The rest of the bulky waste, approx. 1.4 million Mg, respectively, was material recycled. A high percentage of the bulky waste consisted of wood. The material recycling of wood is, from the global warming potential point of view, not useful, because only small amounts of GHG emissions are released during deforestation and in the sawmill. Only a negligible 0.004 Mg of $CO_{2,eq}$/Mg were avoided [19]. Some metals were recovered from the recycled bulky waste material, but no exact data is available, so no GHG balance could be calculated.

In total, the separate collection and treatment of bulky waste avoided approx. 0.53 million Mg of CO_2 equivalents.

4.7 Residual Waste

The separate waste types not collected in household waste are disposed of as mixed residual waste. In Germany in 2014, a total of approx. 14.2 million Mg were collected. Approx. 11.9 million Mg were directly incinerated in waste incineration plants, and approx. 2.3 million Mg were treated in MBTs [14]. With the calculated substitution factors of 0.039 Mg of $CO_{2,eq}$/Mg mixed residual waste in waste incineration plants and 0.015 Mg of $CO_{2,eq}$/Mg for the MBT path (see also Fig. 8), the waste incineration avoided approx. 0.46 million Mg of CO_2 equivalents and the MBT path of approx. 0.04 million Mg.

In total, the treatment of the mixed residual waste avoided approx. 0.5 million Mg of CO_2 equivalents in 2014.

4.8 WEEE and Other Separately Collected Waste Fractions

In Germany, in addition, almost 0.6 million Mg of waste electric and electronical equipment (WEEE) and almost 2.3 million Mg of other waste fractions like composites, metals, and textiles were separately collected. No reliable data about recovered secondary materials and or GHG substitution factors for the treatment processes are available in the literature. Therefore, in this article, no further calculations were made. But the high content of valuable materials and the high GHG substitution potential of provided secondary materials already expect large quantities of avoided GHGs.

4.9 Comparison of Separately Collected Waste Amounts and Their Potential to Reduce Greenhouse Gases

As described in the previous chapters, the amounts of separately collected wastes do not correspond to the amounts of avoided GHG emissions. Figure 10 shows the comparison between the amounts of separately collected waste types and their corresponding amount of avoided GHG emissions in Germany for 2014.

The comparison shows that the separate collection of glass had the best performance in terms of reduction of GHGs. With 5% of the collected waste amount, approx. 18% of the avoided GHG emissions were realized (substitution factor: 0.414 Mg of $CO_{2,eq}$/Mg). With 13% of the separately collected waste amount, the treatment of packaging waste achieved 25% of the overall avoided GHG emissions (substitution factor: 0.245 Mg of $CO_{2,eq}$/Mg). The separate collection of paper and

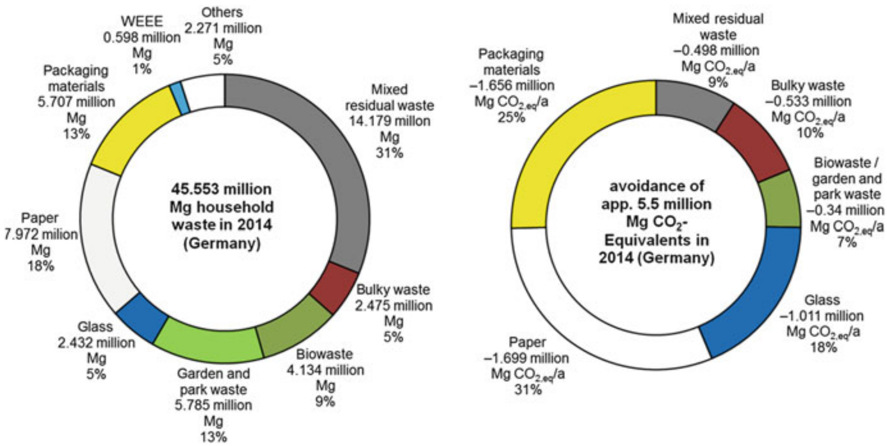

Fig. 10 Comparison of separately collected waste amounts and their amounts of GHG emissions avoided

bulky waste reaches equal efficiencies with substitution factors around 0.215 Mg of $CO_{2,eq}$/Mg. The treatment of the mixed residual waste with a share of 31% of all collected waste avoided 9% of the overall emissions avoided (substitution factor: 0.035 Mg of $CO_{2,eq}$/Mg), and the biowaste/degradable garden and park waste (23% of the amount and only 7% of the avoided GHG emissions and a substitution factor of only 0.036 Mg of $CO_{2,eq}$/Mg) delivered the worst results.

Finally, it can be stated that the treatment of all separately collected wastes results in a negative GHG balance, or in the avoidance of GHG emissions. The energy and/or the secondary materials that were recovered in each case avoided more GHGs as released by the treatment processes.

5 Comparison of the Different Waste Treatment Options

Household waste can be collected as mixed waste in one bin, and environmentally sound waste disposed of in sanitary landfills, thermally treated in waste incineration plants, or mechanically and biologically/physically treated in mechanical-biological/physical treatment plants (see Sect. 3). As an alternative, different waste types can be separately collected and treated to recover more secondary materials and to thermally treat the material which is not possible to recycle. Figure 11 shows, as a result, the comparison of the GHG balances of these four basic options for the treatment of German household waste in 2014.

The comparison shows that the separate collection of different waste types and their individual treatment in Germany performs, with a GHG substitution factor of in average 0.129 Mg of $CO_{2,eq}$/Mg, better than all three other options of mixed waste collection and treatment. In total, approx. 5.5 million Mg of CO_2 equivalents were avoided by the separate waste collection and treatment in Germany in 2014.

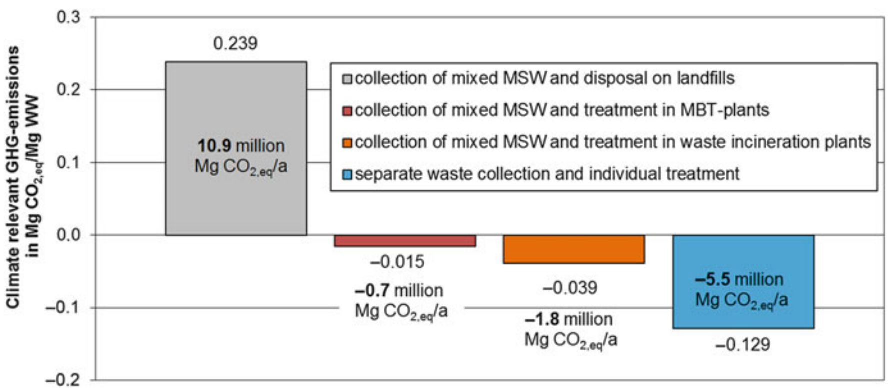

Fig. 11 Comparison of GHG net emissions of different treatment options for 45.6 million tons of mixed and separate collected wastes. Numeric values above and below the columns represent the substitution factors

6 Summary and Conclusions

With the actual German conditions, the treatment of separately collected household waste performs better than the treatment options of mixed household waste. Only small amounts of valuables (generally metals) are recovered if mixed waste is treated in MBTs or waste incineration plants. The recovery of energy is more in focus, but at the moment, the efficiency of energy recovery in Germany for waste incineration plants, and also for RDF plants, is for both relatively low. With higher efficiencies, especially with a higher recovery rate of heat in the form of delivered steam and/or district heat, the thermal treatment options (waste incineration and MBT with thermal utilization of the produced RDF) can reach the amount of avoided GHG emissions of the separate waste collection and treatment.

Also, for the separately collected waste fractions, there is potential for improving the treatment to recover more materials and energy, e.g., only 25% of the separately collected packaging waste is finally transferred to secondary materials; approx. 75% is finally incinerated/thermally treated.

The production of compost from the separately collected biowaste and biodegradable garden and park waste avoids only very small amounts of GHG emissions. In terms of reducing GHGs, the incineration of this material would be much more efficient. Here, the discussion of climate protection versus resource efficiency starts. In terms of the recovery of nutrients like phosphorus to conserve resources, biological treatment and compost production are very useful.

It is also important to mention that the GHG balance is only one aspect of a decision-making process. For environmental protection, aspects like ozone depletion or acidification also have to be taken into account (LCA). And finally, economic factors/drivers often influence the decision of a collection and treatment system.

From the authors' point of view, the separate collection of different waste types is part of a modern waste management system, and only with source separation or very efficient (and expensive) material recovery facilities can secondary materials be recovered in high qualities to save natural resources and avoid high amounts of GHG emissions.

Finally, it should be noted that China, with more than 1 billion Mg/a of household waste, has a huge potential for the recovery of secondary materials and a high potential to avoid GHGs.

References

1. Globales Emissions-Modell Integrierter Systeme (2017) GEMIS version 4.95
2. Gromke U, Detzel A (2006) Ökologischer vergleich von büropapieren in anhängigkeit vom faserstoff. In: Auftrag der initiative pro recyclingpapier. Institut für Energie- und Umweltforschung Heidelberg GmbH, Heidelberg

3. Patel M (1999) KEA für produkte der organischen chemie – erarbeitung von basisdaten zum energieaufwand und der umweltbelastung von energieintensiven produkten und dienstleistungen für öko-bilanen und öko-audits. Fraunhofer-Institut für Systemtechnik und Innovationsforschung (FhG-ISI), Karlsruhe
4. Verein Deutscher Ingenieure (2012) VDI 4600, Cumulative energy demand (KEA) – terms, definitions, methods of calculations. Beuth Verlag, Berlin
5. Simon FG, Holm O (2016) Exergetic Considerations on the recovery of metals from waste. Int J Energy 19(3):352–363
6. Fritsche UR, Hochfeld C, Jenseit W, Rausch L, Lützkendorf T, Eiermann O, Kohler N, Ziesing HJ, Patel M (1999) KEA: mehr als seine zahl – basisdaten und methoden zum kumulierten energieaufwand (KEA): im Auftrag des umweltbundesamtes
7. Thorneloe SA, Weitz A, Nishtala SR, Yarkoshy S, Zannes M (2002) The impact of municipal solid waste management on greenhouse gas emissions in the United States: technical paper. J Air Waste Manage Assoc 52:1000–1011. ISSN: 1047-3289
8. Ketelsen K, Kanning K (2006) ASA-strategie 2030 - ressourcen- und klimaschutz durch eine stoffspezifische abfallbehandlung - herausforderungen, chancen, perspektiven. Im Auftrag der ASA e.V. – Arbeitsgemeinschaft Stoffspezifische Abfallbehandlung, Hannover
9. Hoffmann G, Wünsch C, Schnapke A, Schingnitz D, Baumann J, Brunn L, Günther M, Wagner J, Bilitewski B (2011) Nutzung der potenziale des biogenen anteils im abfall zur energieerzeugung. Im Auftrag des umweltbundesamtes, Dessau-Roßlau. ISSN: 1862-4804
10. Interessengemeinschaft der thermischen abfallbehandlungsanlagen in Deutschland e.V.: ITAD Jahresbericht 2013
11. Fehrenbach H, Giegrich J, Schmidt R (2007) Ökobilanz thermischer entsorgungssysteme für brennbare Abfälle in Nordrhein-Westfalen. Im Auftrag des ministeriums für umwelt und naturschutz, landwirtschaft und verbraucherschutz des landes Nordrhein-Westfalen, Düsseldorf
12. Verein Deutscher Zementwerke e.V. (2015) Environmental data of the German cement industry, Düsseldorf
13. Reimann DO (2012) Results of specific data for energy, R1 plant efficiency factor and net calorific value (NCV) of 314 European WtE plants. CEWEP, Energy Report, III (status 2007–2010)
14. Statistisches Bundesamt: Umwelt – Abfallbilanz (Abfallaufkommen/verbleib, abfallkennzahlen, abfallaufkommen nach wirtschaftszweigen) 2014 (2016) Statistisches Bundesamt, Wiesbaden
15. Schüler K (2016) Aufkommen und verwertung von verpackungsabfällen un Deutschland im Jahr 2014, Iim Auftrag des Umweltbundesamtes, Dessau-Rosslau. ISSN: 1862-4804
16. Springer C (2010) Vom substitutionspotential und der energiebilanz des komposts zum entwurf eines effizienzpasses für biologische Abfallbehandlungsanlagen, Disserstation, Bauhaus-Universität Weimar
17. Kehrens B (2012) Klima-contra ressourcenschutz, in Humuswirtschaft & Kompost aktuell, Ausgabe 3
18. Voigt R, Knappe F, Lazar S, Höke S (2012) Optimierung der verwertung organischer abfälle, im auftrag des umweltbundesamtes, Dessau-Rosslau. ISSN: 1862-4804
19. Dehoust G, Schüler D, Voigt R, Gierich J (2010) Klimaschutzpotenziale der abfallwirtschaft – am beispiel von siedlungsabfällen und Altholz. Im Auftrag des Umweltbundesamtes und des Bundesverbandes der Deutschen entsorgungswirtschaft e.V., Dessau-Rosslau. ISSN: 1862-4804

Part IV
Future of Source Separation

40 Years of Source Separation in Germany and Its Future

Bernd Bilitewski

Abstract In the early 1970s of the last century, new sorting and pyrolysis plants as well as new ideas for landfills were introduced and constructed. The result of this was a separate collection, recycling and reuse of material, and energy recovery from waste of more than 90% in a number of cities and areas in Europe.

What kinds of problems are we facing that we should solve in the future sooner rather than later? Today in our modern society, we need more than 90% of all known elements in our consumer products and produce a severe environmental problem. This makes a proper recycling and reuse of especially rare elements very difficult and a real challenge.

Chemicals are ubiquitous. Once man-made chemicals enter the environment, they can move around regionally and worldwide through a variety of mechanisms. High toxic concentrations can be found (in predator species and human beings).

The new threat is coming from closing the loop at a global scale. Plastic, paper and cardboard, lubricants, electronic devices, nano-coated material, and other products undergo a recycling process and make their way into a recovered material with unpredictable and unforeseen health and safety problems.

This is what we have to solve in the future.

Keywords Circular economy, Health risks, Limitation of recycling, Recovered material

Contents

B. Bilitewski (✉)
INTECUS GmbH, Dresden, Germany
e-mail: bilitewski@intecus.de

R. Maletz et al. (eds.), *Source Separation and Recycling*,
Hdb Env Chem (2018) 63: 291–296, DOI 10.1007/698_2017_33,
© Springer International Publishing AG 2017, Published online: 29 July 2017

1 Introduction

In the early 1970s of the last century, with the start of modern waste management, an important and innovative push came from the USA. New sorting and pyrolysis plants, as well as new ideas for landfills, were introduced and constructed. Germany followed soon also, with new ideas and newly developed technologies. The result of this was a separate collection, recycling and reuse of materials, and energy recovery from waste of more than 90% in a number of cities and areas in Germany. This has been a very big success, but even so, we still face certain environmental problems awaiting a solution.

2 The Pattern of the Circular Economy

In 1996, the German parliament passed the law on Kreislaufwirtschaft (Circular Economy), and since then a number of criticisms created a demand for a revision of the law. The conventional linear perception of the economic system is converted into a circular system with a number of regulations and laws, as shown in Fig. 1.

The German government was guided by the following principles:

- Waste and pollution prevention is the primary objective of the development of a circular economy. Prevention can be achieved through a change in technology to achieve cleaner production.
- Better reuse and waste recycling. Better and more recycling-friendly products should be demanded to fulfill higher recycling rates.
- Gradual introduction of new economic patterns of production. Reuse and recycling have to be established. Economic tools like producer responsibility, tax and charging policies, tax deductions, etc. need to be established.
- Mobilization of the whole of society to establish a new pattern of consumption, reuse, recycling, and avoidance of waste.
- Development of a legal framework to promote the circular economy.
- Complete ban on the use of landfills – everything has to be recycled.

The most innovative development in the area of material recycling was the implementation of automatic identification units on the basis of X-rays, NIR, TV cameras, etc. Near-infrared sensors ["NIR"] analyze materials or do an analysis of their molecular structure. Rapid camera systems identify the shape, surface, and/or color. But different camera types identify waste components by opacity or transmission. "CMYK" sensors were developed to distinguish printing inks with Cyan, Magenta, Yellow, and Black to sort paper (Fig. 2).

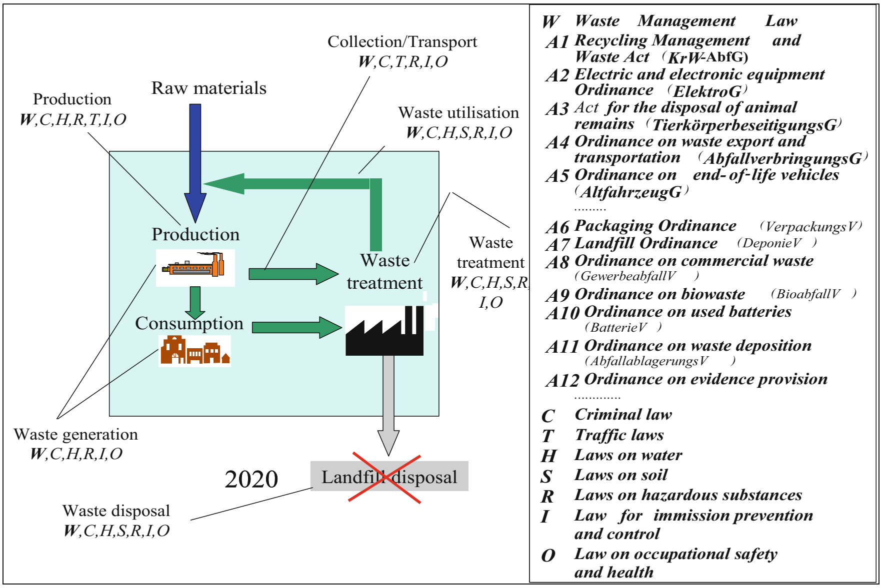

Fig. 1 Schematic figure of target areas of balanced material flow in a circular economy [1]

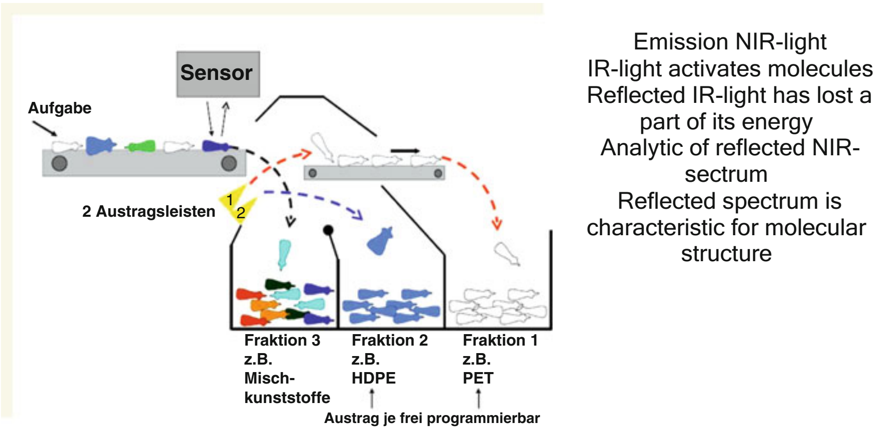

Fig. 2 Schematic figure of automatic sorting machine for plastic [1]

3 Limitations of Recycling

The limitations have already been mentioned. The most important of these is the limitation of technically closing a material loop completely. Only very few materials such as glass and metal and other inorganic components could possibly make a complete loop become reality. Organic matters like paper, plastics, or all other organic molecules undergo a degradation process over time and during a recycling process, so that the quality will deteriorate (down recycling).

Figures 3a, b show the influence of recycling on energy consumption or costs of a new product. In Fig. 3a, the resulting slope shows that recycling can effectively replace virgin material up to more than 50%. In Fig. 3b, the costs of waste management are added. The resulting curve of all three cost curves in Fig. 3b shows that the waste management costs have a significant influence on the amount of recycled material. The higher the waste management costs, the greater the volume of materials recycling will be, which is also a positive indicator for the introduction of a landfill tax. The limitation of this system is also quite clear. As soon as the resulting curve leaves its optimal point and reaches the level of the virgin material costs, then recycling is no longer preferable for the given circumstances.

I would like to introduce a second severe problem affecting the worldwide material flow of recyclable pollutants in waste fractions.

What kinds of problems are we facing that we should solve in the future sooner rather than later? I can demonstrate it with the periodic system. Almost 200 years ago, only very few elements were used, like iron, copper, lead, tin, gold, silver, etc. Out of all of the elements, we used less than 10%. Today in our modern society, we need more than 90% of all known elements in our consumer products and are creating a severe environmental problem. This makes the proper recycling and reuse of especially rare elements a very difficult and a real challenge.

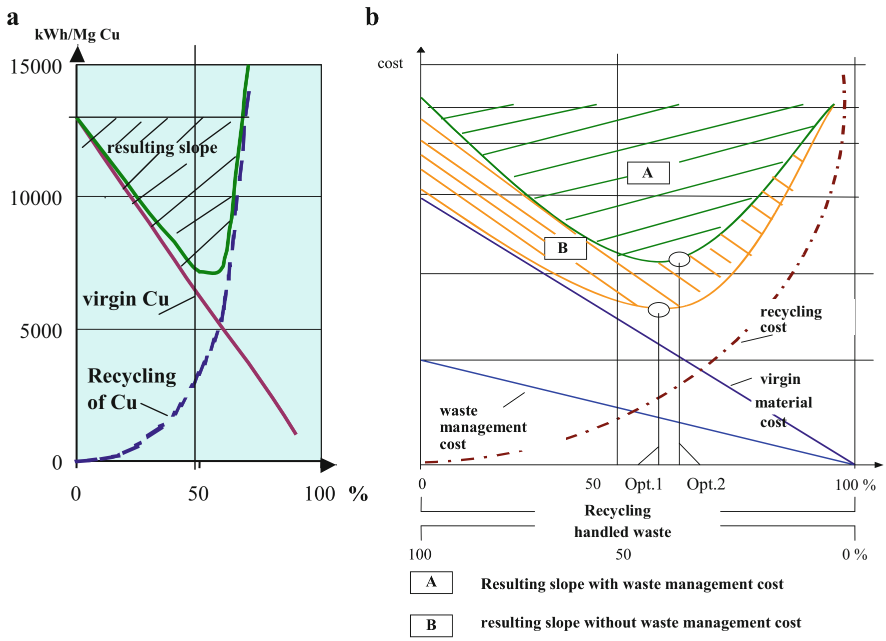

Fig. 3 The influence of recycling (**a**) plus waste management (**b**) on the use of virgin material [2]

Chemicals are ubiquitous. Everything in our world is made of chemicals, including all living organisms, our food, the water we drink, and the air we breathe. In addition to the interactive mixture of natural chemicals, human activity has added more than 100,000 different new chemicals, of which about 30,000 are used regularly in industrial processes. Some are known to be harmful to humans, to wildlife, and to the environment, but for others, toxicity and eco-toxicity data are not available.

Once man-made chemicals enter the environment, they can move around regionally and worldwide through a variety of mechanisms. Some react with light or other chemicals, some are degraded and form new dangerous molecules, and others persist for many decades. Following ingestion by living organisms or uptake by plants, some chemicals can become bioaccumulated and become more concentrated as they move up the food chain. Highly toxic concentrations can be found in predator species and human beings.

In spite of some common efforts to harmonize the safety assessment of chemicals and products, a new problem with recovered materials has also appeared. Recycling as it is done today is producing a problem in a circular economy at global scale, with its risks for health and the environment as a consequence of the worldwide trade of chemicals and products. The new threat is coming from closing the loop at a global scale. Plastics, paper and cardboard, lubricants, electronic devices, nano-coated materials, and other products undergo a recycling process and make their way into recovered material with unpredictable and unforeseen health and safety problems.

This is what we have to solve in the future.

References

1. Bilitewski B (2006) From waste management to circular economy, workshop on circular economy at the National University of science Hanoi
2. Bilitewski B (2007) Environment and peace: balancing development and environmental protection, conference at the University of Seoul

Success Factors for the Implementation of Separate Collection Systems

Roman Maletz

Abstract Within the symposium "Waste Reduction and Recycling: Challenges and Trends for Source Separation," which was held from June 6 to 10, 2016, participants discussed the successful implementation of separate collection. The conclusions of this symposium are summarized in this chapter and consider some additional aspects. It is focused on the situation in China and Germany, but they are also applicable to different situations and regions around the world. For countries with rising waste management challenges, source separation has been proven to be one of the fundamental solutions for the sustainable handling of resources and achievement of a circular economy. The driving forces for establishing of efficient collection schemes are described in this chapter, referring back to the previous chapters of the book, where the challenges and possibilities for different fractions and separation technologies are presented.

Keywords Collection scheme, Developing countries, Recycling, Source separation, Success factors, Waste management

Contents

R. Maletz (✉)
Institute of Waste Management and Circular Economy, Technische Universität Dresden, Dresden, Germany
e-mail: roman.maletz@tu-dresden.de

R. Maletz et al. (eds.), *Source Separation and Recycling*, Hdb Env Chem (2018) 63: 297–314, DOI 10.1007/698_2017_51,
© Springer International Publishing AG 2017, Published online: 9 July 2017

1 Introduction

In the symposium “Waste Reduction and Recycling: Challenges and Trends for Source Separation,” which was held from June 6 to 10, 2016, participants discussed the successful implementation of separate collection. The conclusions of the symposium summarized in this chapter consider some additional aspects. The conclusions and summarized results from this book focus on the situation in China and Germany, but can also be applicable to different situations and regions around the world.

Separate collection is seen as one of the most important instruments to reducing residual waste streams and therefore reducing the landfilling of waste (e.g., see [1–5]). Landfilling leads to land consumption, landfill gas emissions (see [6]), and the depletion of resources that could instead be looped back into the economy through recycling and recovery.

Source separation reduces the GHG balance of a country (see [7]), avoids land consumption, and can lead to regional economic benefits using locally recycled materials instead of imported raw materials (see [8]). These benefits were described in the previous chapters. The conditions needed to implement and run a separate collection system should be highlighted in this concluding chapter.

Actually, it can be divided between success factors for source separation itself, measured by ecological and economic parameters, and success factors for the implementation of new waste management schemes. In this paper, separate collection schemes for countries which have no or rudimentary segregation systems are meant.

Before looking at the success factors, some different kinds of source separation schemes are shown briefly again (for further information on the different types, see [9–11]), because the collection scheme is one of the most influential factors in the amount of resultant recycling material.

2 Separate Collection Schemes

European countries (besides Japan) have one of the most developed source separation systems in the world. Therefore, as an example, the systems of 28 EU capitals have been investigated by BIPRO/CRI [12]. According to their system, the performance of the systems differs. The possible configurations used in the different EU capitals are shown in Fig. 1.

The systems can be classified by *collected single fractions* and *collection type*. Usually relevant single collected fractions are: biowaste, paper, plastic (or sometimes used for packaging waste), metals (sometimes included in packaging waste), and WEEE.

For implementation planning also of high importance is the collection type, which means: collection at the household level, bring points (recycling points) or civic amenity cites (i.e. recycling yards) (see also [11]). Differences for the German situation are shown in Table 1.

<table>
<tr><th>Collection type</th><th>Paper</th><th>Glass</th><th>Plastic</th><th>Metal</th><th>Bio-waste</th></tr>
<tr><td>Door-to-door (single fraction)</td><td>AT, BE, BG, CY, DE, DK, FI, HU, IT, LU, LV, NL, SI, UK</td><td>BG, FI, LU, LV, NL, SI, MT</td><td>AT, LV, NL, DK</td><td>FI, NL, DK</td><td>AT, BE, CZ, DE, FI, EE, IT, HU, LU, NL, SI, SE, IE, UK</td></tr>
<tr><td>Co-mingled ...plastic + metal</td><td></td><td></td><td colspan="2">BE, BG, CY, DE, FR, IT, HU, LU, SI</td><td></td></tr>
<tr><td>...3 fractions</td><td colspan="4">RO, MT: paper, plastic, metal
UK: plastic, metal, glass</td><td></td></tr>
<tr><td>...all in one bin</td><td colspan="4">EL, IE: paper, glass, plastic, metal</td><td></td></tr>
<tr><td rowspan="2">Bring points</td><td rowspan="2">CZ, EE, ES, FR, HR, LT, PT, PL, SE, SK</td><td rowspan="2">AT, BE, DK, CY, CZ, DE, EE, ES, FR, HR, IT, HU, LT, PT, PL, RO, SE, SK</td><td>SE</td><td>AT, EE, SE</td><td rowspan="2">ES</td></tr>
<tr><td colspan="2">ES, HR, LT, PT, PL
(all plastic/metal in one container)</td></tr>
<tr><td>Civic amenity sites</td><td colspan="5">Primary collection: CZ (metal waste), SK (metal and bio-waste), LV (metal)
Addition collection of all waste streams: all countries
PL: rare distribution of civic amenity sites</td></tr>
</table>

Fig. 1 Overview of collection systems in place in the 28 EU countries (primary systems only), source: BIPRO/CRI [12]. *AT* Austria, *BE* Belgium, *BG* Bulgaria, *CY* Cyprus, *CZ* Czech Republic, *DE* Germany, *DK* Denmark, *EE* Estonia, *EL* Greece, *ES* Spain, *FI* Finland, *FR* France, *HR* Croatia, *HU* Hungary, *IE* Ireland, *IT* Italy, *LT* Lithuania, *LU* Luxemburg, *LV* Latvia, *MT* Malta, *NL* Netherlands, *PL* Poland, *PT* Portugal, *RO* Romania, *SE* Sweden, *SI* Slovenia, *SK* Slovakia, *UK* United Kingdom

Table 1 Differences for the German situation, investigation by Dehoust and Christiani [13], no misthrow with a bring system is assumed

	Pickup system kg/(cap*a)	Bring system kg/(cap*a)
Average collection yield	30	11
Average sorting residuals of yield	10	–
Balance	20	11

Table 2 Collection schemes implemented in Germany as the standard system or as pilot projects (each color stands for one bin at the household level), derived from Schröer et al. [14]

<table>
<tr><th rowspan="2">Concept</th><th rowspan="2">Bio waste</th><th colspan="2">Residual waste</th><th rowspan="2">Packaging waste</th><th rowspan="2">Small WEEE</th><th rowspan="2">Paper cardboard</th><th rowspan="2">Glass</th></tr>
<tr><th>No valuables</th><th>Valuables</th></tr>
<tr><td>Standard bin configuration</td><td></td><td colspan="2"></td><td></td><td>Civic amenity site</td><td>Bin/bring points</td><td>Bring points</td></tr>
<tr><td>Packaging waste in the residuals bin</td><td></td><td colspan="3"></td><td>Civic amenity site</td><td>Bin/bring points</td><td>Bring points</td></tr>
<tr><td>Dry valuables bin</td><td></td><td></td><td colspan="2"></td><td>Civic amenity site</td><td>Bin/bring points</td><td>Bring points</td></tr>
<tr><td>Valuables bin plus small WEEE ("Yellow bin plus")</td><td></td><td></td><td colspan="3"></td><td>Bin/bring points</td><td>Bring points</td></tr>
</table>

According to the specific situation in the collection area and underlying waste management strategies, different combinations and numbers of household bins and other collection spots are possible with the most successful solution. For Germany, the concepts introduced in the last several years as pilot projects are shown in Table 2.

2.1 Two-Bin System

Another possibility is the two-bin system, which could be a compromise between the collection effort and separation of clean and dry valuables.

Waste is collected in two bins, a so-called dry bin, which contains recyclable material like plastic packaging, metals, textiles, minerals, and other non-sticking or wet material. The wet bin contains the biowaste fraction, including garden waste and residuals with high moisture content like diapers and hygienic products. There have been several research attempts at implementing a double-bin system in Germany, but the advantages of this system haven't been clear enough for widespread establishment [14], or the differing interests of market players. Under different conditions, a double-bin system could be effective regarding the different aims of national waste management programs. Introducing segregation systems step by step, it seems appropriate to start with the most economic and ecologically relevant waste stream to extract in one separate bin.

2.2 Three-Bin System

When three bins are used for household collection, usually the fractions of residual waste, biowaste, and a valuables fraction are collected separately. The understanding of valuables differs from country to country. Especially in Germany, the valuables bin is for collecting packaging that mostly consists of plastic and metal packaging. This collection and recycling system is paid for by the packaging producers according to an extended producer responsibility system.

2.3 Four-Bin System

Collection of four different single fractions at the household level requires a well-developed waste management system like the one found in Germany. Due to several investigations, this evidently does not lead to the best recycling efficiency because of the influence of some other factors which should be described in Sect. 3 (Fig. 2).

2.4 Commingled System

When commingled collection systems are used, different valuables are gathered in one mixed (commingled) material stream instead of the separate collection of high-quality mono fractions (See [11]). This can often be seen in countries or municipalities that do not have the economic power to establish more bin collection

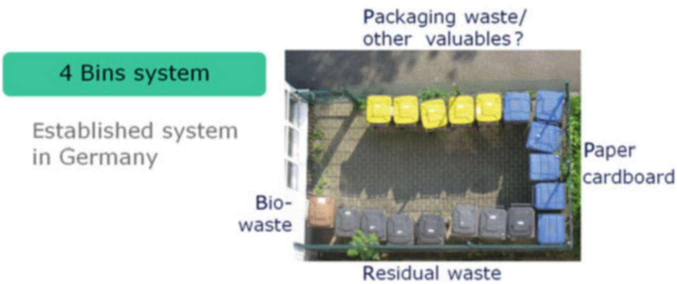

Fig. 2 The most common collection scheme in Germany (door-to-door collection of packaging waste, paper/cardboard, residual and biowaste)

systems, among other reasons like availability of space and public collection behavior and awareness.

3 Success Factors for Implementation

Before separate collection can be implemented successfully, certain prerequisites are required. The chosen waste streams have to be technically recyclable and available with a high share in the original waste stream (see [11]). The design of products in the chosen waste stream must allow for the accessibility of the relevant valuable materials [15]. For example, plastic products like packaging should consist of different, easy-to-segregate types of plastic. Furthermore, it is important to establish a comprehensive collection, at least for the European situation, but can be carried over to a situation with rudimentary collection systems. Another factor is the need for transparent and valid data [15]. Only with reliable data are secure planning and investment calculations possible. For collection schemes in Europe or well-developed urban areas in China, respectively, that are already established, it is useful to orient toward the best-performing recycling infrastructures for further progress and optimization. At this level of implementation there are challenges regarding the effectiveness and efficiency and what the optimal technical and organizational set-up of the whole recycling chain is [15].

For rural areas, a survey about the introduction of source separation was carried out, which is described in [16]. The authors found out that important success factors include a share of awareness, convenience and sufficient separation facilities, and the willingness to pay. Furthermore, it has been proven for the rural study area in China that annual household income and location significantly influence the willingness to pay (see [16]). Also, the political entities can support the implementation process by funding the desirable behavior of the public (subsidizing schemes for municipalities or incentive systems for households to participate).

3.1 Separation of the Most Suitable Waste Streams

In this book, the relevant material streams for segregation are considered in [17, 18] (biowaste), [19] (WEEE), and [20] (plastics). This section focuses on the separation of biowaste seen as one of the most effective opportunities. It is necessary under pervasive economic limitations to concentrate on the most economic valuables, which allow the reduction in the environmental effects in the most eco-efficient way, i.e. the reduction of environmental damage at the lowest cost.

Looking worldwide, the major waste management challenge is the reduction in landfill gas emissions. Separating organic waste as the main part of household wastes could reduce these emissions the most. Ensuring the degradation of organic

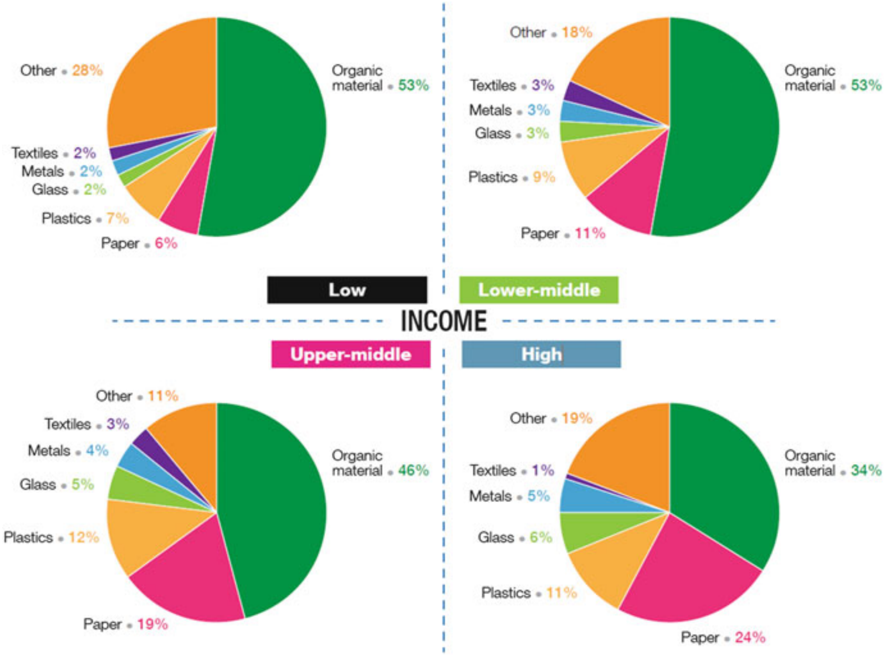

Fig. 3 Average national composition of household wastes depending on the different socioeconomic status goals, taken from [4] generated from other sources

material under controlled conditions in composting plants avoids methane gas production within landfills (see [6]).

Furthermore, the separation of biowaste from the residual waste stream leads to a decrease in water content, and therefore to an increase in dry matter in the residual waste stream.

Looking at waste compositions in countries all over the world, biowaste has the largest share in the overall generation (see Fig. 3).

Two of the major UNEP waste management goals are to cut food waste generation and food losses during production in half, respectively. Biowaste handling therefore seems to be one of the big issues in introducing waste separation schemes [4].

3.2 Qualities of Output

For established recycling markets, increasing the efficiency of separation systems by improving the qualities of the sorting products is one of the biggest challenges. Due to the calculation of recovery rates by input material amounts, recycling facilities concentrate on increasing their input amounts to generate high revenues for reception rather than the effort of high prices for good quality recycling material, especially in the case of Germany.

How prices for waste management tasks influence the waste management situation of a country is shown in [21].

For other collection schemes with a high share of informal collectors and therefore a high share of manual sorting, the quality issues are particularly regulated by the trade relations between the sorting people and the buying companies. The better the quality provided by the separation and recovery chain, the less environmental-political regulations are necessary. This can be seen in established, well-functioning trading systems of valuable materials all over the world in regions with large informal sector activities. This obviously occurs in missing or underdeveloped national waste management systems (see also Sects. 3.5 and 3.6).

As an example, for securing the quality of recycling material, the current Chinese policy of the "National Sword" can be mentioned [22]. It is intended to prevent the illegal smuggling of bad-quality recycling material, especially plastics such as WEEE. The campaign is the continuation of "Operation Green Fence" – the Chinese government effort to ensure high quality (uncontaminated material) for the recycling market, among other objectives like preventing illegal imports of household and hazardous wastes.

3.3 Role of Waste Incineration

It is scientifically proven that waste incineration does not necessarily impede recycling implementation efforts. In [23], some conclusions were made about the suitable combinations of recovery of materials and energy.

As can be seen in [7], it was mentioned that the same amounts of GHG could be saved by recycling and incineration processes. Following developments in Europe, a combination of high-efficient waste incineration for materials not suitable for recycling together with a focus on eco-efficient recycling turns out to be the best allocation between the interests of climate change mitigation, avoiding waste disposal hazards and using material cycles for enabling the best working circulating economy. For this, a blanket ban on landfilling is not seen as expedient, but rather the implementation of subsidies for efficient waste-to-energy technology and recycling products (Recommendations from [3]).

3.4 Separation Technology

Separation technology is evidently necessary for efficient segregation and to ensure high-quality recycling output, which is needed for an economically feasible recycling industry (see [10, 11, 17]).

The most innovative development in the area of recycling was the implementation of automatic identification units on the basis of X-ray, NIR, TV cameras, etc. (see [21]).

The technical factors for economically feasible material recovery are comprehensive collection in the coverage area. In Germany, the daily collection rate for packaging waste ranges from 0.02 to 0.2 kg per capita per day (7–80 kg/year) [13]. Causes are seen in different regional consumer habits and varying socioeconomic conditions.

3.5 Integration of the Informal Sector

The informal sector still plays an important role in Chinese rural and metropolitan areas. Scavengers often collect recyclables at the source. Residents sell their recyclables to buyers at the household level door-to-door. Beneath that, the informal waste collection and marketing of related streams takes place at every stage of the waste handling process. This practice strongly influences the flow of the waste stream [24]. For the urban regions in China, informal recycling rates were estimated in the range of 17–38% [25]. But there is a lack of scientific information about the informal waste sector in China. It can be assumed that the informal sector decreases due to the increasing level of organized waste management in all Chinese regions.

3.6 Measures for the Strict Enforcement of Legislative Regulations on Source Separation

Though a law came into force in China in 2008 prohibiting plastic bags, its implementation cannot be sufficiently controlled.

Punishment is necessary, as stated by Prof. Li Yong during the roundtable discussion at the Shanghai Workshop. If there are no other economic incentives for the stakeholders (e.g., public or recycling companies), pushing the mechanism via legislation should provide support. This could mean rewarding systems for avoiding residual waste or the enactment of recycling laws as they are found in Europe. For German waste legislation systems and the measures included for the implementation of source separation schemes in the 1990s, see [26].

3.7 Summary of Success Factors

In Table 3 the most important success factors are sorted by different categories like policies, waste characteristics, technical, economic, and social aspects. The factors

Table 3 Factors and their conditions for enabling eco-efficient implementation (adapted from [15, 27]), the chapters of this book and the roundtable discussion at the 2016 Shanghai workshop

	Factor	Success requirement level for implementation	Successful condition/ description	Percent of case studies as a barrier	Source
1	Government policy	Medium	Presence of regulations, enforcement of laws, and use of incentive schemes	63	[27]
2	Legislation/ monitoring/ enforcement	Medium/high	External factor, which especially is needed in situations with low economic incentives for implementation itself	n. considered	Hagelüken [15], stated by Chinese Waste Management Professors during roundtable discussion
3	Government finances	Medium/high	Cost of operations, budget allocation to MSWM, stability/reliability of funds	77	[27]
4	Landfill tipping fee	Very high	The rise of the tipping fee is seen as the starting point for European Separate Collection schemes	n. considered	[21]
5	Waste characterization	Medium	Assessment of generation and recovery rates, and composition of waste stream	67	[27]
6	Waste collection and segregation	High	Presence and efficiency of formal or informal collection and separation by scavengers, the municipality, or private contractors	79	[27]
7	Collection infrastructure	Medium/high	Efficient and convenient collection systems, amount of waste trucks, recycling points, bin distribution, etc.	n. considered	[15]

(continued)

Table 3 (continued)

	Factor	Success requirement level for implementation	Successful condition/ description	Percent of case studies as a barrier	Source
8	Separation technology	Medium/high	Especially for countries with well-established Waste Management Systems a high standard of recycling technology leads to high and good quality output rates	n. considered	[21]
9	Household education	Medium/high	Extent of knowledge of waste management methods and understanding linkages between human behavior, waste handling, and health/sanitation/environment within households	69	[27]
10	Household economics	Low	Individuals' income influencing waste handling behavior (reuse, recycling, illegal dumping), presence of waste collection/disposal fees, and willingness to pay by residents	22	[27]
11	Stakeholder behavior and motivation (consumers/ emotional link, OEMs/EPR culture, retailers, recyclers)	Medium/high	Identification of the stakeholders with	n. considered	[15]

(continued)

Table 3 (continued)

	Factor	Success requirement level for implementation	Successful condition/ description	Percent of case studies as a barrier	Source
12	MSWM administration	Medium	Presence and effectiveness of private and/or public management of waste (collection, recovery, disposal)	44	[27]
13	MSWM personnel education	Medium/high	Extent of trained laborers and skilled professionals in MSWM positions	83	[27]
14	MSWM plan	Medium	Presence and effectiveness of an integrative, comprehensive, long-term MSWM strategy	50	[27]
15	External collection incentives (e.g., leasing, deposits, etc.)	High	The higher the amount subsidized recycling prices the more stakeholder groups will involve in the business	n. considered	[15]
16	Local recycled material market	High	Existence and profitability of market systems relying on recycled-material throughput, involvement of small businesses, middlemen, and large industries/ exporters	36	[27]
17	Material value	High	Intrinsic factor, good quality with low impurities/ contaminations leads to profitable prices for recycling material	n. considered	[15]

(continued)

Table 3 (continued)

	Factor	Success requirement level for implementation	Successful condition/ description	Percent of case studies as a barrier	Source
18	Qualities of output	High	Higher quality leads to better prices and to more acceptance by the users of recycling material, which leads to more economic feasibility	n. considered	Section 3.2
19	Separation of the most suitable waste streams	High	Concentration on the dominant or most economic waste streams is the most cost efficient way to solve the major challenges like reducing disposal amounts and enable economic feasible waste management	n. considered	Section 3.1
20	Business model/lifecycle type (B2C, B2B)	High	Intrinsic factor, handling of B2B recycling material enables high purities	n. considered	[15]
21	Complexity/ heterogeneity (product composition and design)	Low	Recyclability of collected waste material	n. considered	[15]
22	Technological and human resources	Medium/high	Availability and effective use of technology and/or human workforce and the safety considerations of each	58	[27]
23	Land availability	Low	Land attributes such as terrain, ownership, and development dictating MSWM	0	[27]

(continued)

Table 3 (continued)

	Factor	Success requirement level for implementation	Successful condition/ description	Percent of case studies as a barrier	Source
24	Role of waste incineration	Medium/low	WI do not impede source separation, can be established together like in Europe	n. considered	Section 3.3
25	Integration of the informal sector	Medium/high	Integration leads to better working conditions for workers and enables access to the valuable material streams out of the informal sector	n. considered	Section 3.5

shown are collected from this book or referring to literature sources and show the success factors both for implementation and the running of separation or recycling systems, too.

Each factor is assigned to an "importance" or "success requirement" level. It can be seen that some factors are more required than others. In this author's assessment it is shown that economic factors like presence of the demand for recycling products or the material value push recycling, because there informal or formal business structures arise. Troschinetz and Mihelcic [27] assessed some factors by a survey of stakeholders in different developing countries. The stakeholders had to evaluate the barriers for establishing sustainable recycling. In this survey the highest rated factor was the education and experience of the involved MSW staff and decision makers.

The interdependencies of the 12 factors detected by Troschinetz and Mihelcic [27] are shown in Fig. 4. It can be seen that the most connections are around factor 4 (presence of a waste collection and segregation system). This proves that successful implementation is a mandatory basis for a sustainable waste management system.

4 Conclusion

The main driving force to implementing waste minimization and cleaner technologies, and to exploit waste economically and feed it back into the production cycle, is the price of the final waste disposal, as Prof. Bilitewski emphasized during the roundtable discussion at the end of the workshop. It means that the main factor for

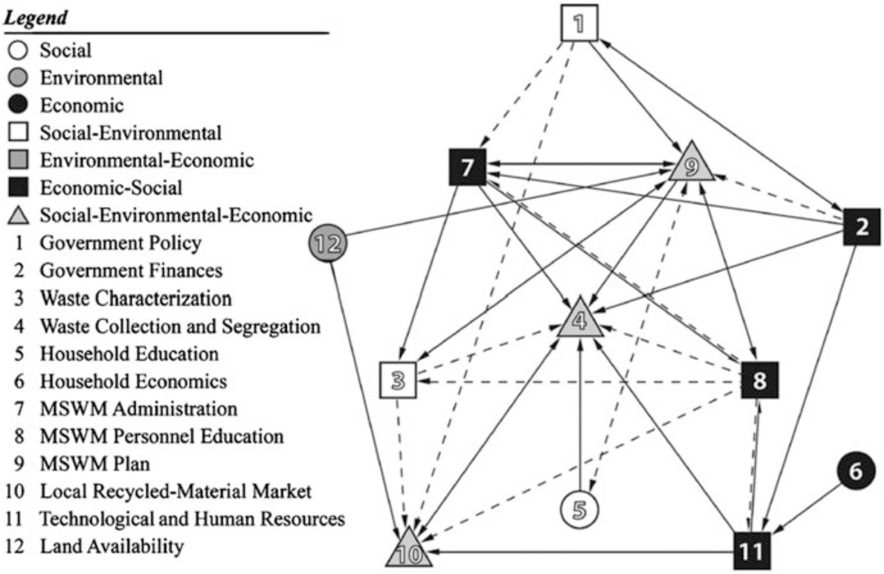

Fig. 4 Collaboration web illustrating relationships among the 12 factors influencing sustainable recycling in developing countries. There are institutions responsible for each factor's activities. A *solid line* represents necessary collaborating institutions for a given factor to contribute to sustainable recycling, whereas a *dashed line* implies a heightened influence on sustainable recycling by a given factor upon institutional interaction. *Arrows* show how information flows from one MSWM institution to another; this defines the stakeholder involvement required of each party. *Node shading* and *shape* identify the sustainability dimensions governing MSWM institutions' responsibilities based on relationships among factors. Copied from [27]

successful implementation is naturally the costs. The implementation of cost-covering source separation schemes leads to rising waste fees. So only with rising opportunity costs for sanitary landfilling or other disposal operations can this financial effort be equalized.

Economic viability could be ensured by intrinsic or extrinsic factors. In market-driven societies like in Germany, intrinsic factors like the monetary value of recycled material outputs traded on the recycling market often are insufficient for the increasing of recycling activities. Costs that are too high compared to the prices of virgin materials impede a relevant substitution by such materials. Therefore, some extrinsic factors like the environmental policies are needed to encourage a comprehensive implementation of the separation of waste streams. The promotion of recycled materials could be one example. The Electronic Product Environmental Assessment Tool (EPEAT) could be mentioned as an example. EPEAT comes from the Green Electronics Council in the United States, and is the leading assessing organization of environmental lifecycle standards. The program evaluates computer desktops and laptops, monitors with 51 environmental criteria, and awards EPEAT Bronze, Silver or Gold certifications. EPEAT now covers 43 countries, over 60 participating manufacturers and more than 4,400 environmentally preferable electronic products [28].

The combination of these factors can lead to successful implementation at an improved eco-efficiency and ecological effects that are not intrinsic drivers for the implementation of source separation.

5 Overall Conclusion

For China and other countries with rising waste management challenges, source separation has been proven to be one of the fundamental solutions for the sustainable handling of resources and achievement of a circular economy.

The separation of the biowaste stream from the residual waste flow can be seen as the most important, easiest, and most effective way of reducing waste amounts for landfills, especially for current conditions in China. This could be stated for Germany and other European countries, too, with sophisticated collection systems and raised experience over several decades. But, especially in Germany, the increase in separated biowaste handling in Germany has slowed down because of the competitive situation between using the renewable energy content of biowaste during the residual waste treatment and the underlying industrial interests. Of importance is the consideration of national and regional conditions when trying to implement source separation. Over and above that and finally said, moving toward a low waste economy, i.e. pushing waste reduction in general, is the most environmental and economic path that has to be re-proven in the coming years under the paradigm of sustainability.

References

1. Dehoust G, Schüler D, Vogt R, Giegrich J (2010) Climate protection potential in the waste management sector – examples: municipal waste and waste wood. Report by order from the Federal Environment Agency of Germany
2. Fischer C (2013) Municipal waste management in Germany. Official country report for the European Environment Agency
3. Hogg D, Ballinger A (2015) The potential contribution of waste management to a low carbon economy – main report. Eunomia Research & Consulting, Bristol
4. Wilson DC, Rodic L, Modak P, Soos R, Rogero AC, Velis C, Iyer M, Simonett O (2015) Global waste management outlook, Geneva. ISWA report ordered by the UNEP. ISBN: 978-92-807-3479-9
5. Vogt R, Derreza-Greeven C, Giegrich J, Dehoust G, Möck A, Merz C (2015) The climate change mitigation potential of the waste sector. Report by order from the Federal Environment Agency of Germany
6. Ziyang L, Zhilin X, Zhaowen C, Tiantao Z, Bofeng C (2017) The waste management system in China and greenhouse gas emission inventories. Handb Environ Chem. doi:10.1007/698_2017_32

7. Wünsch C, Simon FG (2017) The reduction of greenhouse gas emissions through the source-separated collection of household waste in Germany. Handb Environ Chem. doi:10.1007/698_2017_35
8. Friege H (2017) Separate collection of waste fractions – economic opportunities and problems. Handb Environ Chem. doi:10.1007/698_2017_24
9. Nassour A et al. (2017) Separation by manual sorting at home: state of the art in Germany. Handb Environ Chem. doi:10.1007/698_2017_26
10. Schingnitz D (2017) Separation of MSW in treatment plants (MBT). Handb Environ Chem. doi:10.1007/698_2017_27
11. Clausen A, Althaus M, Pretz T (2017) Commingled waste collection as chance for technical separation – alternative collection systems. Handb Environ Chem. doi:10.1007/698_2017_29
12. Seyring N, Dollhofer M, Weißenbacher J, Herzog M, McKinnon D, Bakas I (2015) Assessment of separate collection schemes in the 28 capitals of the EU. Final report, Nov 2015. BIPRO/CRI
13. Dehoust G, Christiani J (2012) Analyse und Fortentwicklung der Verwertungsquoten für Wertstoffe (Analysis and further development of recovery rates for valuables). Report by order from the Federal Environment Agency of Germany
14. Schröer R, Morgan RM, Urban AI (2007) Nasse + trockene Restabfalltonne Ein neues System für Kassel? (Wet and dry bin – a new system for the city of Kassel?). In: Urban AI (ed) Weiterentwicklung der Abfallwirtschaft (Further development of waste management), vol 7. UNIK-AT, Berlin, pp 111–122
15. Hagelüken C (2016) Circular economy for metals – chances, challenges and limitations (German). Presentation at 23rd colloquium of waste management and contaminated sites, Dresden, 3 Nov 2016
16. Chao Z, Hangfen L, Fafa X, Dongjie N, Youcai Z (2017) Source-separated collection of rural solid waste in China. Handb Environ Chem. doi:10.1007/698_2017_30
17. Fricke K, Heußner C, Hüttner A, Turk T (2017) Recycling of biowaste experience with collection, digestion and quality in Germany. Handb Environ Chem doi:10.1007/698_2017_34
18. Long Y, Shen D (2017) The effect of source separation on the waste disposal process: case study in Hangzhou. Handb Environ Chem. doi:10.1007/698_2017_31
19. Salhofer S (2017) E-waste collection and treatment options: a comparison of approaches in Europe, China and Vietnam. Handb Environ Chem. doi:10.1007/698_2017_36
20. Kuchta K (2017) Circular economy opportunities for plastic. Handb Environ Chem
21. Bilitewski B (2015) Years of source separation in Germany and its future. Handb Environ Chem. doi:10.1007/698_2017_33
22. Perchard E (2017) China starts National Sword campaign to target ‘foreign waste’ smuggling. Press report from 23rd February 2017. www.resource.do. Accessed 27 Feb 2017
23. Quicker P (2017) Thermal treatment as a chance for material recovery. Handb Environ Chem. doi:10.1007/698_2017_28
24. Zhang DQ, Tan SK, Gersberg RM (2010) Municipal solid waste management in China: status, problems and challenges. J Environ Manag 91:1623–1633
25. Linzner R, Salhofer S (2014) Municipal solid waste recycling and the significance of informal sector in China. Waste management and research, vol 32. Sage, London, pp 896–907
26. Dornack C (2017) Waste policy for source separation in Germany. Handb Environ Chem
27. Troschinetz AM, Mihelcic JR (2009) Sustainable recycling of municipal solid waste in developing countries. Waste Manag 29:915–923
28. EPEAT (2016) http://www.epeat.net. Accessed 13 Dec 2016

Index

R. Maletz et al. (eds.), *Source Separation and Recycling*,
Hdb Env Chem (2018) 63: 315–318, DOI 10.1007/978-3-319-69072-8,
© Springer International Publishing AG 2018