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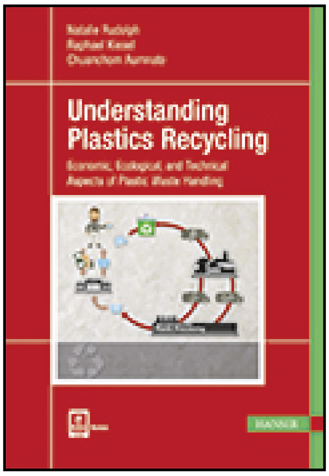

Sample Pages

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Understanding Plastics Recycling

Economic, Ecological, and Technical Aspects of Plastic Waste Handling

Book ISBN: 978-1-56990-676-7

eBook ISBN: 978-1-56990-677-4

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Preface

Thank you for taking the time to read this book on plastic recycling. We hope you benefit from reading our summary and research regarding this topic. With different backgrounds and states in our scientific careers, we are united by the interest in using our knowledge to educate and make the world a little better—one topic and one word at a time.

It all began when I had started as an assistant professor at the University of Wisconsin-Madison and a new potential graduate student was sitting in front of me to discuss our collaboration. With many topics in my head and finally a position where I could explore topics close to my heart, Chuanchom Aumnate wanted to work on recycling of plastics. I thought to myself that I should probably still wait some more years with such a topic, get more established first, and then start working on it.

But in reality, I could not resist and we started formulating a project. Our aim was to focus on a topic that would make an impact and could solve problems around the globe. We decided to start with plastic packaging, due to its huge worldwide market share, and wanted to investigate the necessity of sorting, a process which is still immature for typical packaging materials and therefore limits the amount of recycled plastic.

Thus we worked on blending of typical packaging materials like polypropylene and polyethylene as an alternative for the sorting process to increase the amount of recycled plastic waste. We used scientific as well as industrial tests to analyze the resulting material properties. Our goal was to identify promising combinations as well as practical test methods for their analysis.

Very early on we realized that in addition to our technical study, we needed to understand the cost benefit of eliminating the sorting process and compare it to both conventional recycling and other waste management strategies. We could expand our work when Raphael Kiesel, on a scholarship from Germany, came to UW-Madison and decided to work on this topic. He combines the solid technical and business background needed to look at all of those aspects in combination. Soon after Raphael started on the topic, we realized that all of us were driven by understanding recycling holistically—including the technical, economic, and ecological advantages and disadvantages.

The idea for the book was born from my colleague and mentor, Prof. Tim A. Osswald, when he attended Raphael's Master defense and suggested that we should publish our very interesting analysis in a book to reach a broader audience. And this is what we did.

We compiled our own analysis results together with data from other research groups and summarized it in the present book.

The book starts with a general overview of waste handling strategies and their shares of the U.S. market are presented (Chapters 1 and 2). In Chapter 3 special focus is placed on the technical aspects of recycling for various applications and specific polymers.

In separate chapters their economic (Chapter 4) and ecological value and costs (Chapter 5) are evaluated and compared. The analysis shows the advantages of plastic recycling as well as the necessary boundary conditions for future growth. In Chapter 6 different scenarios to increase the profitability of recycling are analyzed and blending of plastic materials is identified as a suitable strategy.

Last but not least, the findings for the U.S. are put into context to the worldwide potential for waste handling and in particular plastic recycling using Europe and China as examples in Chapter 7. All the data and calculations presented in the book and summarized in the tables in the Appendix in Chapter 8 can be downloaded as spreadsheets for the reader's own analysis and updates in a fast changing economy.

Thus, the book is an entry level book for decision makers in the plastics industry as well as students, researchers, and industry experts new to the field of plastic recycling.

True to our mission, this book is printed on recycled paper. We hope you enjoy reading it.

Madison, March 2017 *Natalie Rudolph*

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directly related to the price of virgin resins for that type of plastic, which is related to the price of oil (see Section 4.4.5). Low oil prices result in low costs for the virgin resins. In these times, recycled resins are too expensive to be used by comparison, and the recycling rates drop. Therefore, the goal of any sustainable growth in recycling should be the maximization of efficiency of energy utilization in every step of the process, from the initial production of plastic goods to the disposal or recovery of plastic wastes. [2]

3.1 Plastics Recycling Methods

There are three common methods for plastics recycling: *mechanical recycling* (primary and secondary recycling) and *chemical recycling* (tertiary recycling). Based on the degree of contamination of the plastics (Section 3.5) with organic or inorganic substances (other polymers or impurities), one of these three recycling methods is chosen. The molecular structure of the plastics as well as existing cross-links, such as in thermosets or rubbers, also influence the decision process. [3, 4]

3.1.1 Mechanical Recycling

Amongst the recycling methods, mechanical recycling is the most desirable approach because of its low cost and high reliability. In general, mechanical recycling keeps the molecular structure of the polymer molecule basically intact. After grinding of the plastics waste material, the main processing step is remelting of the regrind material, which limits the use of mechanical recycling to thermoplastic polymers. Since remelting causes a degradation of the polymer chain, virgin material is often mixed with recycled material to reduce the effects of degradation on the product properties. The mixing leads to a dilution of the virgin material, which is described in Section 3.2.1.2. [5]

Mechanical recycling is divided into primary and secondary mechanical recycling, depending on whether the source of the waste is preconsumer or postconsumer, respectively. Preconsumer manufacturing scrap plastic is usually clean and of a single type or at least of a known composition and requires no further treatment, whereas postconsumer waste is highly contaminated and requires additional steps like collecting, sorting, and cleaning.

3.1.2 Chemical Recycling

Chemical recycling is used for *cross-linked polymers* or for thermoplastic polymers if no sufficient quality can be achieved using mechanical recycling. Chemical processes are used to convert the polymer chains to *low molecular weight* compounds or, in some cases, the original plastic monomer (feedstock). The monomers can be used for polymerization to generate the original polymer again, whereas the low molecular weight compounds are used as feedstock for the petrochemical industry. Common processes for this recycling method are hydrolysis, hydrocracking, and depolymerization. Because of the large amounts of energy and chemicals consumed by these processes, chemical recycling is only economically and ecologically reasonable for a very limited number of polymers such as polymethyl methacrylate (PMMA) and polyether ether ketone (PEEK). Chemical recycling of polyethylene terephthalate (PET) has been successfully developed. However, it is hindered by the processing cost. Furthermore, the chemical processing has been proven to be technically possible for polyolefins but is still in the laboratory stage of development. [3, 4, 6, 7, 8]

■ 3.2 Recycling Different Types of Plastic Waste

As mentioned before, plastic waste can be divided into *preconsumer waste* (manufacturing scrap) and *postconsumer waste* (recovered waste). These different plastic waste types are recycled differently.

3.2.1 Preconsumer Waste

3.2.1.1 Manufacturing Scrap

Preconsumer waste, such as runners, gates, sprues, and trimming, is normally recycled using primary mechanical recycling. It is ground and remelted in-house.

3.2.1.2 Dilution Effect

Manufacturing scrap is often mixed into virgin material to reduce material cost while at the same time minimizing the effects of degradation on part performance. Depending on the mixing ratio, either the virgin material is diluted with regrind or the regrind is refreshed with virgin material. By using a constant mixing ratio during continuous processing, the regrind waste itself is diluted by material that has been reprocessed once, twice, three times, etc. The composition of a material with a proportion of recyclate q after n processing cycles can be calculated using Equation (3.1).

$$\sum_{i=1}^{n} q^{n-i}(1-q) = 1 \tag{3.1}$$

For small proportions of recyclate, the regrind material contains only minimal amounts of material that has passed through a large number of processing cycles and therefore is highly degraded.

Figure 3.1 shows the composition of material with different mixing ratios of recycled and virgin material. The first column shows 30 % recycled and 70 % virgin material. Under these conditions, the regrind material contains less than 0.8 % of material that has been reprocessed five times or more. Seventy percent of the material is virgin material, 21 % has been processed once, 6.3 % twice, and 1.9 % three times. As proportions of material smaller than 1 % do not have a significant influence on the material properties and can be neglected [9], the properties will be dominated by fractions that have been processed four times or less. Thus, it can be concluded that the properties of a material with small amounts of recyclate will not fall below a certain level. [10]

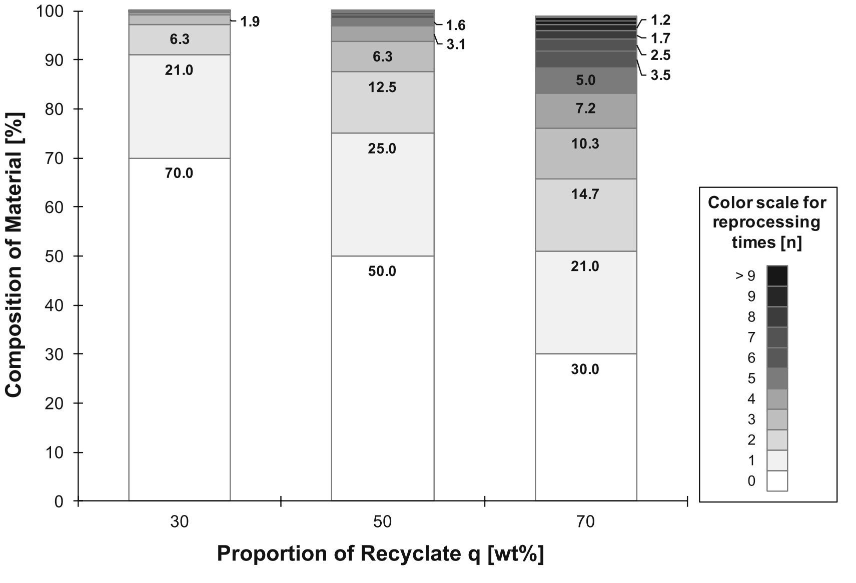

Figure 3.1 Composition of recycled plastics material after n reprocessing steps for 30 %, 50 %, and 70 % recycled material

Another controversial subject of waste-to-energy plants, more than any other plastic handling method, is noise. Trucks bringing solid waste to the facility, plant operations, and fans are sources of noise pollution. [21]

The biggest issue of burning plastic is the generation of pollutants, especially CO_2. Since plastic is created from a fossil fuel, its combustion is considered an anthropogenic source of carbon emissions. An EPA study revealed that incinerators are the dirtiest electricity production option, releasing more greenhouse gases than coal-fired power stations per unit of energy generated.

Table 5.1 shows the *net emission factor* for combustion of 1 t of high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polyethylene terephthalate (PET) in metric tons of a carbon dioxide equivalent ($MtCO_2E$)[1] calculated using the EPA's *Waste Reduction Model (WARM)*. This factor includes the emissions associated with transporting (903 km per shipment) the plastic waste to WTE facilities and emission savings associated with the avoided emissions of burning conventional fossil fuels for utilities. It shows that the production of greenhouse gases through waste combustion is much higher than the emission savings. [11, 22]

Table 5.1 Net Emissions Factor Due to Combustion for Various Plastics

Material	Transportation to Combustion [$MtCO_2E$/t]	CO_2 from Combustion [$MtCO_2E$/t]	Utility Emissions Avoided [$MtCO_2E$/t]	Net Emissions Factor [$MtCO_2E$/t]
HDPE	0.033	3.075	−1.664	1.444
LDPE	0.033	3.075	−1.664	1.444
PET	0.033	2.249	−0.871	1.411

CO_2, dioxins, and particles contribute to negative effects for the environment, such as climate change, smog, and acidification, and for the human body, such as asthma, lung damage, cardiac problems, and nervous system damage. [15, 23]

5.3 Environmental Analysis of Recycling

The recycling rate of plastic materials in 2013 was 9.2 %, much lower than the recycling rate of the general MSW (34.2 %). Despite this low rate, plastic recycling has a big positive ecological impact: it provides opportunities to reduce quantities of waste requiring disposal, oil usage, and carbon dioxide emissions. [16, 24]

[1] $MtCO_2E$ (metric tons of carbon dioxide equivalent): This describes how much global warming a given type and amount of greenhouse gas causes using the equivalent of CO_2 as a reference.

Recycling of plastics means waste reduction. In 2013, the total plastic waste produced was 35.5 million tons. Even at the relatively low recycling rate of 9.2 %, it means 3.27 million tons were neither landfilled nor burned, thus not polluting the environment. [16, 25]

Furthermore, plastic recycling is equivalent to the reuse of scarce resources, especially oil. Nowadays, plastics are almost completely derived from petrochemicals, which are produced from fossil oil and gas. Since manufacturing of plastics also requires energy, a similar additional quantity of fossil fuels is used for their production. Reprocessing plastics is consequently the same as reuse of this important resource. [24]

The key benefit of recycling plastic is *the reduction of required plastics production:* less production means less energy use, which simultaneously leads to the reduction of CO_2 and greenhouse gas emissions. Considering the difference between the energy use for producing virgin PET and HDPE and for reprocessing these products at the end of their life, recycling only these two plastics in the United States could save enough energy each year to power 750,000 homes. [26]

Table 5.2 Net Emissions Factor Due to Combustion and Energy Savings for Recycled versus Virgin Plastics

		HDPE	LDPE	PET
Virgin input [$MtCO_2E/t$]	Process energy	1.560	1.905	1.796
	Transportation energy	0.036	0.036	0.036
	Process non-energy	0.172	0.172	0.100
Recycled input [$MtCO_2E/t$]	Process energy	0.118	0.118	0.118
	Transportation energy	0.045	0.045	0.045
	Process non-energy	—	—	—
Savings by recycling [$MtCO_2E/t$]	Process energy	− 1.442	− 1.787	− 1.678
	Transportation energy	0.009	0.009	0.009
	Process non-energy	− 0.172	− 0.172	− 0.100
	Total savings	**− 1.605**	**− 1.950**	**− 1.769**

Table 5.2 shows the difference between emissions from manufacturing 100 % virgin material and 100 % recycled material, calculated using the WARM method, which breaks down the emission into

- Process energy emissions
- Transportation emissions
- Process non-energy emissions

It can be seen that manufacturing of recycled HPDE, LDPE, and PET significantly reduces GHG emissions compared to producing the same amount of virgin material. Among these plastics, LDPE recycling shows the largest GHG emission savings. [11, 26]

Reduction of waste, energy use, and GHG emissions are several positive effects of recycling plastics on the environment. These positive ecological impacts are reflected in the EPA's waste management hierarchy, which superordinates recycling to incineration and landfilling of plastics waste. [16, 25]

5.4 Conclusion: Environmental Necessity of Plastics Recycling

Considering all waste handling options from an ecological point of view, it has been established that recycling clearly is the best way to handle plastic waste. Besides the reduction of waste, it leads to energy savings and decreased GHG emissions.

Recycling is not only a waste management strategy; it further implements the concept of industrial ecology, that there is no waste but only new products. [27]

On this account, the recycling process needs to be improved so that it is both ecologically and economically desirable. Therefore, Chapter 6 will consider two different ways of economically improving the plastics recycling process and making it even more indispensable from an ecological perspective.

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7 Plastic Waste of the World: Increasing Potential of Recycling

In addition to the detailed analysis of the plastics recycling market and its potential future, this book provides an outlook on waste handling and recycling in the global market. In order to understand the global effects of waste generation in general and plastics in particular, differentiating between countries by income is more useful than by geographic region. The following data was collected in the 2012 report on global solid waste management by the World Bank. [1] The numbers are only estimates because the data from some countries was missing, was from different years, and was based on slightly different assessment methodologies. Figure 7.1 shows the dependence of waste generation on income level. Low-income countries produce the least and high-income countries the most solid waste per capita. The wide ranges, such as from 0.7 to 14 kg/capita/day for high-income-level countries, result from disparities within the income-level groups. The waste generated is projected to grow in all geographic areas and income levels due to the increase in population and urbanization. However, the higher the income level of a country, the lower is its projected growth rate of waste generation.

Waste collection is instrumental to access the resources buried inside the waste. However, collection rates vary between 41% in low-income countries and 98% in high-income countries, mainly due to the associated cost of collection. In low-income countries, collection services account for 80 to 90% of the municipal solid waste (MSW) budget. In high-income countries, they can be as low as 10% of the MSW budget. Consumers can be required to separate their waste at the source, such as into different bins, or the unsegregated waste can be separated in sorting facilities. Developing countries use mainly single-stream systems where recyclables are collected by waste pickers during the collection process, starting prior to collection and ending at the disposal sites. In high-income countries, single-stream or multiple-stream systems, such as a combination of curbside pickup and community bins, are used, where collection is frequent and sorting facilities are highly mechanized and efficient. The total amount of recyclables and their quality depend on the degree of separation.

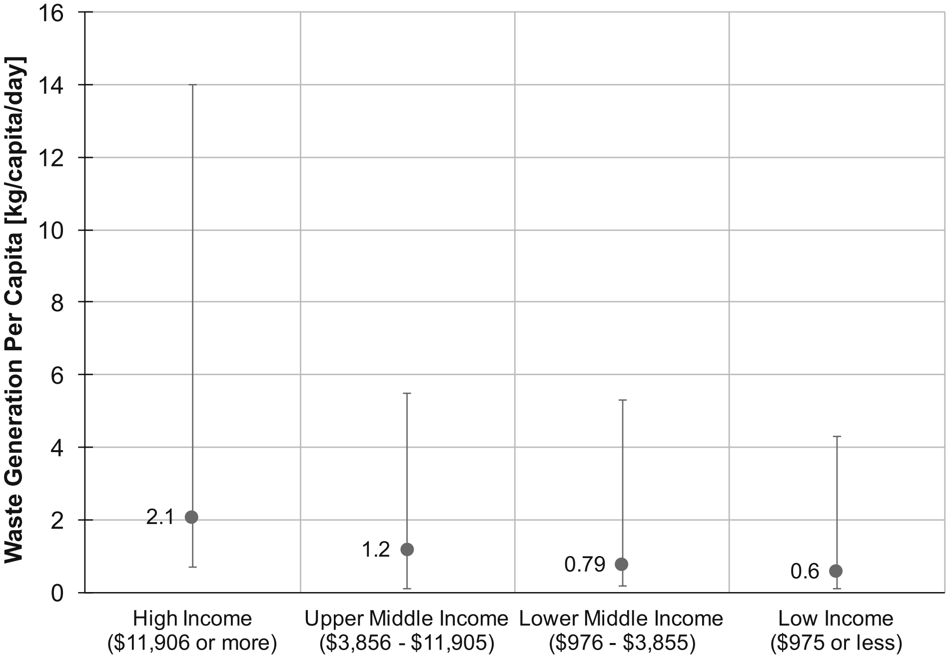

Figure 7.1 Current waste generation per capita by income level (showing the upper and lower limits and the median [dot] waste generation) [1]

The *waste composition* is important to estimate the potential of recycling valuable resources and of energy recovery. Waste composition influences the frequency of collection and disposal and is impacted by factors such as economic development, climate, energy sources, and cultural norms.

As shown in Figure 7.2, the organic fraction tends to be highest in low-income countries and lowest in high-income countries. With progressing urbanization and increase in wealth of a population, more inorganic materials (plastics, paper, and aluminum) are consumed. It is important to note that the total amount of organic waste per capita is on average still 1.5 times higher in high-income countries than in low-income countries. The same is true for all other fractions; for example, the total amount of plastic waste and paper waste is 4.9 times and 22 times higher, respectively. Geography and climate influence the waste composition. It determines the use of building materials (e. g., wood, brick, or steel), horticultural waste, and ash content. The last is related to the predominant energy source as well. Regions where energy for cooking, heating, and lighting is generated by coal and wood fires have a much higher ash content. See, for example, Figure 7.11, which shows the breakdown of waste in China for 2000, where the ash content is included in "Other".

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