Challenges to increase plastic sorting efficiency

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Abstract: The recycling rate for plastics results as a factor, mainly based on multiplying the collection quote, the sorting quote and the recycling process quote of a plastic waste stream. This paper gives insights into sorting rates, challenges to enhance these values and perspective opportunities on how to improve the sorting rate for the future. As a result, the challenges are contrasted with the opportunities to develop future strategies and elevate research necessities to increase the sorting rate.

Keywords: Recycling rate; Sorting rate; Sensor-based sorting; Recycling; Waste treatment; Waste management

Introduction

Plastics are an indispensable part of everyday objects of use and application, both in households and in industry, where they are a central raw material for a wide variety of areas - from packaging material, in medical care, to electronic components, to construction and Transportation Industry - Represent [1]. Around 8.3 billion tons of plastic have been produced globally since 1950. Only nine percent have been recycled; twelve percent were incinerated, and the majority (79%) ended up in landfills or the environment [2]. In 2015, 322 million tons of plastic were produced worldwide [3], and this amount is expected to double by 2035 and quadruple by 2050 [4].

It is undisputed that the resulting plastic waste is an enormous burden for the public and the environment - keyword microplastics in the oceans. Consequently there is an endeavour by business, politics and society to force the recycling of raw materials and to increase the proportion of recovered valuable materials. In this context, recycling rates have the task of providing statistical information on the proportion of waste recycled and fulfilling legal requirements within the framework of national and European sustainability policy. In addition to ecological intentions, economic aspects of recycling must also be considered from a business point of view - the issues of resource efficiency and life cycle considerations in particular, are becoming increasingly important. Bunge [5] states that the usefulness of recycling has to be judged through an economic as well as an ecological perspective. As a recycling rate approaches the 100 percent mark, recycling becomes more and more inefficient in terms of costs/benefits. The ecological yield from recycling increases linearly with the degree of recycling, while the ecological recycling effort increases exponentially [5].

Against this background, questions and hitherto unsolved problems arise concerning the determination and collection of recycling rates, including the extent to which these contribute to sustainable development goals. For example, in plastics recycling, the aim is to show the consequences of rate regulations along the value chain and whether the implementation of such rate can contribute to the recovery of processed material flows. Further, the inherent potential of rate implementation needs to be evaluated.

Framework Conditions for the Definition of Recycling Rates

The Austrian Waste Management Act [6] defines recycling as "any recovery process through which waste materials are processed into products, things or substances, either for their original purpose or other purposes. It includes the processing of organic materials, but not energy recovery and processing into materials that are intended for use as fuel or for backfilling." Accordingly, recycling is recovery, not reuse. Waste is considered completely recycled if it is fed into a process recognized as recycling. No distinction is made between which parts are actually recovered for use as secondary raw materials [7].

Based on the definition mentioned, specific proportions of the reusable or recycling rates are determined but the method of calculating of these rates is open to interpretation, this can yield different outcomes - even within the same material fractions. Further, no specifics for determining the total amount of waste and partial amount of recycling are stated, this leads to different measuring points for each different group of waste, hampering the comparability of results. This lack of definition is further evident in the interchangeable use of the terms “recovery” and “recycling” in official and legal documents, showing the confusion present when discussing the subject.

Recycling Rate – Definition of the Term

In waste management, the recycling targets are based on rates. The essential requirement for calculating a rate is knowledge of the population of the recyclable material available on the market. Uniform definitions and calculation methods are not available at the national level (e.g. differences in federal states) or European Union level. From a global perspective, this raises considerable problems concerning collecting and determining recycling rates against the background of exports (e.g. through packaging materials) [8]. In this context, Bothe [9] states about the dual systems that "a calculation that compares only a mixture ‘x’ with an unknown composition and only partially known whereabouts to a mixture ‘y’ of another and also unknown composition as a reference variable is not even a rate.”

There are two main distinctions to be made when defining recycling rates [7]:

a. **Production-related recycling rate (input-related):** Indicates the recycling rate in the material input of a production process;

b. **Waste-related recycling rate (output-related):** Refers to the proportion of materials or valuable materials recycled from the waste during disposal.

It must be considered that a high waste-related recycling does not necessarily lead to a high production-related recycling rate since the import and export of waste also enable the secondary material to be used in other economies [7].

The following distinction is also essential in this context: While the recovery rate includes the thermal recovery of valuable materials from waste (i.e. the incineration of the same, including their processing into fuel), the recycling rate excludes this type of recovery. Therefore, the recovery rate is greater than the reuse or recycling rate [10].

European and National Case Law on the Rate Regulation for Plastics Recycling

At the European Union level, plastic waste is dealt with through several legal provisions, but none specifically designed for plastic. Plastics are indirectly addressed by the following directives: Waste Framework Directive (2008/98/EC) [11], Directive on waste electrical and electronic equipment (2012/19/EU) [12], Directive on end-of-life vehicles (2000/53/EC) [13], and in the Packaging and packaging waste directive (94/62/EC) [14].

The target for the reuse and recycling of municipal waste is set in Article 11 of the Waste Framework Directive at 50% by 2020 (preparation for reuse and recycling). The rate for preparation for reuse, recycling and another material recovery will be increased to 70% by 2020. The only plastic-specific target in European waste legislation concerns the recycling rate of 22.5% for plastic packaging waste [15].

At the national level, plastic is specifically dealt with in the AWG 2002 or the AWG Amendment Packaging (2013) and the Austrian Packaging Regulation (2014) [16]. In the latter, the recycling rate for plastic packaging is also defined as 22.5% to comply with the EU requirement.

The new amendments to the European waste package came into force on July 4, 2018. The essential elements of the new EU waste law set new binding targets, including an increase in the target rates for the recycling of municipal waste and packaging waste and an adjustment of definitions [17]. Furthermore, new calculation methods for the recycling rate of municipal waste are used to measure the actually recycled waste and make the data comparable. However, these rates mainly relate to quantity and not to quality [8].

Table 1 gives an overview of current and planned recycling rates for plastic packaging material. According to this (EU and national), 22.5% of the mass of plastic packaging placed on the market must be brought into a recycling plant.

Table 1: Overview of current and planned recycling rates for plastic packaging material.

	EU			Austria
	Packaging Directive Article 6	Change Policy of Packaging Directive (2018) Article 1		Packaging Regulation § 5
Year	2009	2025	2030	2014
Recycling rate in %	22,5	50	55	22,5

The currently implemented recycling rate for plastic packaging are less than 30% at the EU level in 2018 [18]; 31% are landfilled, 39% are incinerated [19]. According to the Austrian Waste Management Plan (2017) 33.6% of plastic packaging was recycled in 2015, the recovery rate was 100% [20].

Sustainable Recycling of plastic Recyclates

Thermal recovery should only be considered if qualitative plastic processing is no longer possible, it is essential to focus on the recycling of plastics.

Looking at the value-added lifecycle of plastics recycling in Figure 1, it can be seen that this begins with the consumer as a waste producer (1) and is then treated (2), sorted (3) and recycled (4). In the following steps, the recyclate is fed into a production process (5) by the producer and used by the plastic consumer (6) before the cycle closes with waste generation (1). According to Wilts et al. [7], with the definition of the recycling rate for the waste-related recycling rate (output-related), those plastics available as valuable or materials after the recycling process will contribute to the rate fulfilment.

Due to the lack of a uniform legal definition of the recycling rate, a “non-closing” value chain can nevertheless contribute to positive fulfilment. If a recycler processes a material flow from a plastic collection in his plant, the completion of the processing would be sufficient to contribute to the recycling rate. At the end of the recycling process, plastic granules are obtained to be used for processing into new products. It is currently not legally stipulated in what quality the resulting recyclate should be.

The quality assessment of recyclates shows that the sole focus on recycling rates cannot be expedient to close the value chain. The usability of a manufactured recyclate has to be ensured to guarantee

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sustainable recycling. Recycling rates that are not specific to the material flow contrast the usability of the recovered recyclate, which means that the proportion of primary new plastics in products is a multiple of the proportion of recycled material [20].

This means that every generated recyclate that can be fed into a production process can positively contribute to the recycling rate. Whether the use of a given recyclate results in the production of high-quality or low-quality product is not regulated. Neither is the required proportion of new and recycled plastics fed into a production process regulated. When a small proportion of low-quality recyclate is mixed with a high proportion of new plastics the quality for the production of plastic products can usually be maintained, but without having to guarantee sustainable recycling. Another problem that arises from the poor quality and the volatility of the recyclates is that it is more difficult to find buyers for the secondary raw material produced. Forming a market for plastic recyclates or prices based on the quality of the recyclate also proves to be difficult without statutory quality specifications.

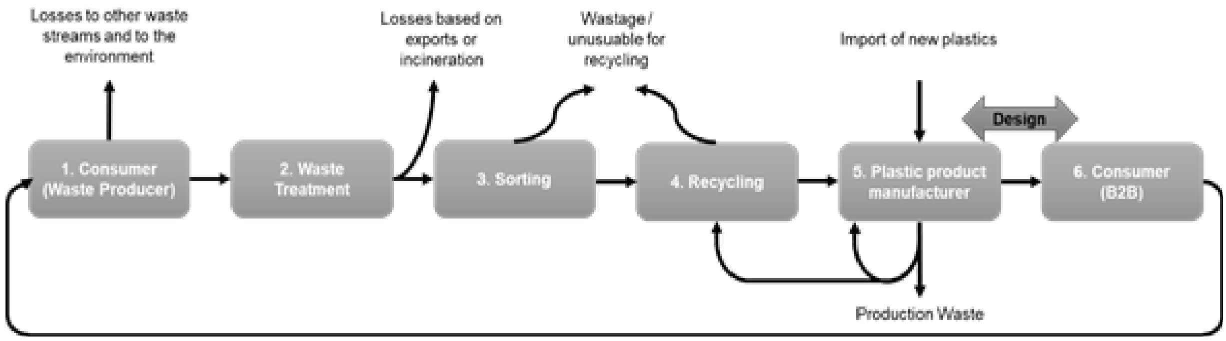

Figure 1: Value-added lifecycle of plastics recycling.

According to Treder [8], the following core requirements must be met in order to solve the rate problem: (1) The definitions of terms and valid data must be standardized, (2) a uniform calculation of rates must be defined. The current procedure for recycling is not appropriate, as it does not consider "high-quality recycling", which can counteract the spread of pollutants. Finally, (3) rates are used to achieve the target if the population (the amount of waste) is known, which is currently not always the case. In addition, it would make sense to adopt rates to dynamic market conditions - e.g. by specifying strategic raw materials - and considering the eco-efficiency of alternative scenarios over the entire life cycle.

Furthermore, an integrated view of economic and ecological aspects over the entire life cycle and the entire supply chain of plastics - from product design to treatment with intermediate sorting and processing systems - is necessary in order to achieve sustainable, resource-efficient waste management and use the possibilities of plastic recycling in an ecologically and economically sensible way.

The Influence of the Sorting Rate on the Recycling Rate

Following Figure 1 it can be seen that there are three types of losses, which negatively influence the output-related recycling rate technologically or socially:

- The **collection rate** is negatively influenced by the losses through incorrect disposal of waste into other waste collection streams like municipal waste or the losses through waste disposal into the environment, mainly known as littering.
- The **sorting rate** is decreased by the losses during the waste sorting process. This includes reject in the last sorting step, wastage, and materials that are unusable for recycling. The lost material during the plastic sorting process is incinerated.
- The **recycling process rate** is reduced by the losses during the recycling process itself based on the wastage and unusable materials for recycling.

Losses caused by exports and incineration are not part of this evaluation because these are regulated politically and are not as affected by technological innovations or social research as other losses mentioned above.

Expecting a collection rate R_{WC} of 70 % for lightweight packaging waste, there are still further losses of 40 % during sorting, which is known as a typical value for the sorting rate R_{WS} and further 40%, which is known as a typical value for the recycling process rate R_{WR} these results in a recycling rate of 25,2% (Formula 1). When the recycling rate of 55 % for lightweight packaging has to be reached by 2030, many steps have to be set.

Since this paper covers only the increase of the sorting rate R_{WS}, it will be expected that a feasible collection rate $R_{WC,}$ for Austria in 2025 is 85 %. The recycling process rate R_{WR} is expected to reach 75 % because of increased process efficiency. This would mean that by 2030, Austria has to increase its sorting rate to 90 % to reach the European goal of a 55 % recycling rate for lightweight packaging waste (Formula 1). Increasing the sorting efficiency to raise the sorting rate is obligatory to achieve this target value.**Status quo:** $R_{WC} * R_{WS} * R_{WR} = 0.7 * 0.6 * 0.6 = 25.2\ \%$

Requirement: $R_{WC} * R_{WS} * R_{WR} = 0.85 * 0.9 * 0.75 = 57.4\ \%$

Formula 1: Calculation of the recycling rate: Status quo and requirement

Challenges and Research Question to be Answered to Increase the Sorting Efficiency

Regardless of the significant, as yet unused secondary raw material potential, there are currently few incentives on the plastics market to increasingly redirect recyclable plastics (mainly polyolefin packaging) from thermal utilization to recycling. Soon, based on the European Union in preparation for the circular economy package [21], a new dynamic in plastics recycling is to be expected. In addition to a gradual increase in the recycling targets for plastic waste, which is currently at 22.5 % should reach 50 % in 2025 and will increase incrementally over the next decade to reach 65 % in 2035. (2020 22.5% | 2025 50% | 2030 55% | 2035 65%, [18]. In addition to the gradual increase of recycling targets, the calculation of the recycling rate will be changed to be based on output related considerations rather than input related considerations.

Increasing the flexibility of the processing technology, concerning the input quality and a growth in the recovery of valuable materials can improve the value-added lifecycle of plastics and the recycling rate.

Additionally, the economic risk in the field of plastic sorting can be reduced.

Fluctuations in the waste stream composition resulting from changes in the collection can be better cushioned with a more flexible processing technology. Furthermore, increased added value can be realized with alternative plastic input streams beyond the packaging plastic.

Through direct processing in the plastics recycling companies after sorting, the value chain can be extended accordingly, or an integration of the value chain of plastic waste sorting and plastic recycling can be achieved.

Challenge: Necessity to Achieve Purities with Possibly Poorer Input Quality

The requirements of the secondary plastics market tend to be higher with the increasing volume of secondary plastics, as is to be expected based on environmental and resource policy requirements. This is due to additional products to be developed for the use of secondary plastics. At the same time, it can be assumed that the quality of the collected plastic waste (input flows for the sorting) becomes worse due to the quantitative goals to be achieved. This development has to be offset by improved sorting technology.

Research question: How can sensor-based sorting processes be improved regarding the identification of known material types?

Challenge: Lack of Structured Knowledge of Complex Products/Material Combinations

Due to a lack of knowledge concerning complex products / material combinations, there are currently no approaches to a differentiated licensing policy based on the recyclability of the system operators of plastic collection and recycling systems. Through a structured gain in knowledge, legislators and manufacturers can be influenced, on the one hand, under the aspect of EcoDesign and, on the other hand, the system operators of plastic collection and recycling systems can establish a differentiated licensing tariff scheme with the corresponding steering effects in the direction of increasing recyclability.

Research question: Which products or material combinations are problematic to be detected, and what are possible solutions to identify them correctly in sensor-based sorting?

Challenge: Increase in the Yield of Recyclable Materials and Purity with Feedback Loops between the Sorting Result to the Plant Operation

The flexibility concerning the sorting input while increasing the recovery of recyclable materials and ensuring the quality of the recyclates required by the secondary raw material market requires the combination of different sorting criteria and their linking within the scope of the sorting decision at a property level. An input-dependent system operation can also ensure that the potential of valuable materials is optimally exploited.

One challenge is the coordinated, clear identification of the signal values provided by various sensors. For clear material identification, signals that sensors can detect must be correlated with specific material properties, which require extensive material investigations on the relevant material systems and access to the sensor-based data. By implementing a feedback loop between the quality of the input and the plant operation, it is possible to adapt the plant operation to the potential of recyclable materials and optimize the recovery of recyclable materials. Such approaches have not yet been implemented.

Research question: How can the sorting efficiency be improved by implementing feedback loops between the sorting result and the plant operation?

The main task for the future is to answer all these research questions with innovative solutions to increase the sensor-based sorting efficiency and further increase the sorting rates to achieve the threshold values of the European recycling goals.

Author Contributions

Conceptualization, Karl Friedrich and Daniel Vollprecht; methodology, Karl Friedrich; validation, Karl Friedrich; formal analysis, Karl Friedrich and Gerald Koinig; investigation, Karl Friedrich and Gerald Koinig; data curation, Karl Friedrich; writing—original draft preparation, Karl Friedrich, Gerald Koinig and Karin Tschiggerl; writing—review and editing, Karl Friedrich, Gerald Koinig and Karin Tschiggerl; visualization, Karl Friedrich; supervision, Daniel Vollprecht and Roland Pomberger; project administration, Roland Pomberger. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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