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Full length article

Influence of plastic packaging design on the sensor-based sortability in lightweight packaging waste sorting plants

Michelle Jakobs [a,b], Nils Kroell [b,c,*]

[a] REMONDIS GmbH & Co. KG, Tonstr. 1, 50374 Erftstadt, Germany
[b] Department of Anthropogenic Material Cycles, RWTH Aachen University, Wuellnerstr. 2, 52062 Aachen, Germany
[c] STADLER Anlagenbau GmbH, Max-Planck-Str. 21, 88361 Altshausen, Germany

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ABSTRACT

Lightweight packaging (LWP) waste is the largest post-consumer plastic waste flow in Germany. A crucial step in plastic recycling is sensor-based sorting (SBS) of LWP in sorting plants. While a more sorting- and recycling-friendly product design is believed to enhance SBS and plastic recycling in general, data to estimate this potential is limited. Here, we aim to quantify the real-world sortability of LWP articles by assessing a SBS cascade for plastic-type separation in a state-of-the-art LWP sorting plant. Our results reveal a polymer-specific distribution of packaging types and quantitatively confirm negative influences of sleeves/labels, composites, dark colors, and rolling shapes on the sortability at sorting plant scale. By extrapolating our results to all LWP sorting plants in Germany, we estimate that up to 48,300 Mg/a (95 % CI: 25,900 Mg/a – 78,500 Mg/a) rigid plastics could be additionally recovered at sensor-based plastic-type separation level alone through improved sortability.

Abbreviations

2D	2-dimensional
3D	3-dimensional
BC	beverage cartons
CI	confidence interval
DSD	Duales System Deutschland GmbH
EPS	expanded polystyrene
Fe	ferromagnetic properties
HD-PE	high-density polyethylene
LWP	lightweight packaging
MP	mixed plastic
NF	non-ferrous metals
NIR	near-infrared
PE	polyethylene
PET	polyethylene terephthalate
PP	polypropylene
PPC	paper, paperboard, cardboard
PS	polystyrene
RQ	research question
SBS	sensor-based sorting
VIS	visible light spectrum
Y	yield

1. Introduction

1.1. Mechanical recycling of post-consumer plastic packaging in Germany

Lightweight packaging (LWP) waste represents the largest post-consumer plastic waste material flow in Europe (Plastic Europe, 2022). In 2021, Germans alone generated about 2.92 million tons of LWP waste (Statistisches Bundesamt [Destatis], 2021). In Germany, LWP waste is collected in a mixed material collection (Wagner et al., 2018) and includes, among others, plastics, metals, and composite packaging (Feil et al., 2021; Kranert, 2017).

In LWP sorting plants, the different plastics contained in LWP waste are sorted by plastic type. In state-of-the-art LWP plants, a distinction is made between polypropylene (PP), polyethylene (PE), polyethylene terephthalate (PET), polystyrene (PS) as well as films and a mixed plastic (MP) fraction (Pitschke and Kreibe, 2020). The sorted products are then fed into different, polymer-specific mechanical post-consumer plastic recycling processes (Pitschke and Kreibe, 2020). The plastic recyclates produced in the recycling processes then re-enter the material cycle and substitute primary plastics in production processes, resulting in notable environmental advantages such as energy conservation and reduced greenhouse gas emissions (Bachmann et al., 2023; Cudjoe et al., 2021).

The correct sorting of plastic packaging in LWP sorting plants is

* Corresponding author at: STADLER Anlagenbau GmbH, Max-Planck-Str. 21, 88361 Altshausen, Germany.
E-mail address: nils.kroell@w-stadler.de (N. Kroell).

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crucial for the overall material circulation as (a) material losses towards energy recovery (sorting residues) cannot be recovered at later sorting stages and (b) suboptimal pre-concentrate purities can lead to additional material losses or suboptimal recyclates qualities in subsequent recycling processes (Dehoust and Christiani, 2012; Knappe et al. 2021; Picuno et al., 2021). Suboptimal recyclate qualities hamper the substitution of primary plastics and thereby limit achievable environmental benefits (Hahladakis and Iacovidou, 2018).

1.2. Research gap: real-world sortability of post-consumer plastic packaging

Correct sorting of post-consumer plastic packaging in LWP sorting plants and thus the overall recyclability of plastic packaging is influenced by both the applied sorting technology (cf. Section 2.2) and the packaging design (Feil et al., 2021; Pomberger, 2020; Knappe et al., 2021; Stiftung Zentrale Stelle Verpackungsregister, 2023). Current assessments of the recyclability of plastic packaging (e.g., Der Grüne Punkt - Duales System Deutschland GmbH, 2023; Bifa, 2019; Verpack, 2021; cyclos HTP, 2023; RecyClass 2020; DIN EN ISO 14021, 2021) often focus only on a theoretical assessment of the recyclability of individual packages, which can differ significantly from the actual recyclability of plastic packaging in real waste management systems (Pomberger, 2020).

In Germany, for example, the recycling of plastic packaging is organized by the dual systems. In the spirit of product responsibility, the dual systems are intended to provide manufacturers with incentives for sorting and/or recycling-friendly packaging design.[1] In accordance with §21 VerpackG, the basic recyclability is considered when calculating the participation fees. To this end, the Zentrale Stelle Verpackungsregister (central agency packaging register) in Germany publishes an annual "Minimum standard for assessing the recyclability of packaging subject to system participation pursuant to section 21 (3) VerpackG" (hereinafter referred to as *minimum standard for packaging design*). The minimum standard for packaging design considers (i) the existence of a sorting and recycling infrastructure, (ii) the sortability of the packaging, and (iii) incompatibilities during recycling.

As shown on the example of the minimum standard for packaging design, it is often assumed that there is a large potential for an improved sorting and thus material circulation based on more recycling-friendly packaging design (e.g., Hahladakis and Iacovidou, 2019). However, since little data has been published on the real-world sortability of post-consumer plastic packaging (cf. Picuno et al., 2021; Schmidt et al., 2021), it is currently difficult to estimate how large this optimization potential is and where exactly (e.g., for which packaging types) the largest potential is to be found.

1.3. Research aims and questions

This publication therefore aims to quantify the real-world sortability of post-consumer plastic packaging in LWP sorting plants and to determine the proportions of different packaging to derive optimization potentials for improved plastic packaging recycling based on a more recycling-friendly packaging design. The investigation will focus on the process stage of *sensor-based plastic-type separation* (cf. Section 2), which has the greatest influence on the overall sorting result of the LWP plant (Feil et al., 2021). To achieve this goal, the following research questions (RQs) shall be answered:

- **RQ 1**: What proportion do different packaging materials and packaging types have in LWP?
- **RQ 2**: Which packaging types are particularly often incorrectly sorted in sensor-based sorting and for what reasons?
- **RQ 3**: How do these findings from RQ 2 correspond to current recommendations for recyclable packaging design (e.g., minimum standard for packaging design in Germany)?
- **RQ 4**: What additional potential of recyclable materials could result from better sortable plastic packaging designs?

2. Background

2.1. LWP sorting plants

There are about 39 LWP sorting plants in operation in Germany, with plant capacities that vary between approx. 20,000 Mg/a to 200,000 Mg/a and a total capacity of 3.3 million Mg/a. (Feil et al., 2021; INTERSEROH Dienstleistungs GmbH, 2022; Kuchta et al., 2023). In addition to the plant capacity, the technical equipment of the plants differs, such that a distinction is made between two groups, LWP sorting plants with and without plastic-type separation (Dehoust et al., 2021).

At REMONDIS' LWP sorting plant in Erftstadt, which will be the focus of the presented case study, up to 120,000 Mg/a of LWP waste are sorted annually (REMONDIS GmbH and Co. KG, 2023). The plant was built according to the state-of-the-art. The collected LWP waste is unloaded and temporarily stored in fully enclosed flat bunkers (Institut cyclos-HTP GmbH, 2021). The plant is fed with a wheel loader or a gantry crane (REMONDIS GmbH and Co. KG, 2023). Bag rippers at the beginning of the sorting process are used for liberating the LWP articles from the collection bags, such that the material is exposed and can be sorted. Comminution and alteration of the article's properties should not take place (Feil et al., 2021).

First, the liberated material passes through four screening stages to narrow down the particle size ranges. In the LWP sorting plant in Erftstadt, a screening drum and three vibrating screens are used for screening (REMONDIS GmbH and Co. KG, 2023). In addition to the separation of different particle sizes, screening has other functions: torn open bags should be emptied and the volume flow should be homogenized (Dehoust et al., 2021).

After screening, the material is wind-sifted by four wind sifters (REMONDIS GmbH and Co. KG, 2023). Thin-walled and flat components are separated here to condition the material flow for subsequent sorting. The light-goods ejection takes place via rotary valves. The heavy fraction is further sorted in the plant (Institut cyclos-HTP GmbH, 2021).

Overbelt magnetic separators are used to separate materials with ferromagnetic properties (Fe). Beverage cartons (BC) are then sorted out using near-infrared (NIR) sorters. This sorting step takes place before the separation of non-ferrous metals (NF) by eddy current separators, as BCs can have an aluminum coating and otherwise be separated into the NF fraction (Feil et al., 2021; Dehoust et al., 2021; Institut cyclos-HTP GmbH, 2021).

A NIR rougher sorts out the plastics contained in the material flow and feeds them to the plastic type separation. During the plastic-type separation, the plastic types of PP, high-density PE (HD-PE), PET bottle, PS, and PET tray are sorted out. The material flow not sorted out by the rougher is fed to a NIR sorter, which sorts out paper, paperboard, and cardboard (PPC). In total, 21 NIR sorters are installed in the LWP sorting plant in Erftstadt (REMONDIS GmbH and Co. KG, 2023; Feil et al., 2021).

Two ballistic separators are used for further material conditioning (REMONDIS GmbH and Co. KG, 2023). Flat 2D materials are conveyed to the upper end by the upward-rotating paddles. Solid 3D materials are separated by gravity at the bottom end. The 3D fraction is sorted in the plastic-type separation (Kranert, 2017; Pretz et al., 2020).

Systematic false rejects from the various sorting steps mean that manual product inspection cannot be completely avoided. Causes can lie

[1] In the context of this paper, we will use the term "sorting-friendly" to describe packaging and products that are designed in a way such that they can be well sorted in real-world sorting plants and "recycling-friendly" to describe packaging and products that are designed in a way such that they can be well recycled in real-world processing plants. Sorting- and recycling-friendliness do not necessarily correlate with each other.

in the product design or plant operation, for instance, material composites or insufficient material separation. In addition, individual products that cannot be sorted out using NIR sorting, such as silicone cartridges made of PE, must be sorted out manually (Institut cyclos-HTP GmbH, 2021).

2.2. Sensor-based sorting in plastic recycling

2.2.1. Fundamentals of sensor-based sorting

Sensor-based sorting (SBS) works according to the principle of single-particle sorting. In SBS, a sensor measures various particle characteristics without contact, such as material composition, color, shape, or electrical conductivity. These particle characteristics are distinguished with the help of various detection methods, such as NIR spectroscopy, inductive sensors, or sensors in the visible light spectrum (VIS). Nowadays, a combination of different sensors is often found, such that several material properties can be detected at the same time (Kranert, 2017).

A SBS unit is made up of several components. The material is passed under a detection unit via an acceleration belt operated at typically 3 m/s (up to 5 m/s with adjusted airflow management) (Kranert, 2017; Feil et al., 2021). A halogen light source installed above the conveyor belt illuminates the material and the radiation reflected from the object surface is measured by the detector. A compressed air nozzle bar is installed at the end of the acceleration belt. If a particle is detected and classified as an eject fraction, the air nozzles are opened with coordinate precision, and the particle is blown out via separation apex through a blast of compressed air. The ejected material stream is called *eject* and the unseparated material stream is called *drop* (Bünemann et al., 2011; Kranert, 2017; Kroell et al., 2022a).

SBS units are often arranged in multiple stages. A *rougher* unit is used as the first sorting stage, with a focus on the highest possible yield of recyclables. Usually, all particles identified as valuable material are sorted out at this stage, which is called positive sorting. The sorted product stream is subjected to a *cleaner* unit, with a focus on generating a high purity of the product stream through negative sorting. Here, all impurities are sorted out of the material flow. The residual streams from both sorting stages are fed to a *scavenger* unit to recover previously incorrectly ejected recyclables through positive sorting (Chen et al., 2023b; Kranert, 2017).

2.2.2. Near-infrared-based sorting of LWP

NIR spectroscopy is one of the most important detection methods in the field of LWP waste sorting (Kroell et al., 2022a; Institut cyclos-HTP GmbH, 2021). It works in the range of NIR radiation in a wavelength range from approx. 780 nm to 2,500 nm, whereas in industrial SBS applications, the wavelength ranges from approx. 1,000 nm to 1,700 nm is used most often (Kroell et al., 2022a; Chen et al., 2023b). The NIR radiation reaches a material-dependent penetration depth of up to 4 mm, such that the surface measurement technology is insensitive to contamination to a certain degree (Bilitewski and Härdtle, 2013). Nevertheless, NIR spectroscopy reaches its limits, for example when sorting dark plastics colored with carbon black, since the light is largely absorbed so that too little radiation is reflected to classify the material (Knappe et al., 2021; Kranert, 2017). In addition, the detection of reflective or metallic surfaces is not possible, as the NIR radiation is reflected non-specifically (Pitschke and Kreibe, 2020).

For optimal SBS, the following requirements must be fulfilled:

(1) Presentation of the material to be sorted as a singled monolayer (i.e., particles do not overlap or touch each other), to ensure that the particles can be distinguished from each other (Kranert, 2017; Kroell et al., 2022a).
(2) Particles must not perform any relative movement on the conveyor belt so that the compressed air blast blows the particles out correctly (Kranert, 2017).
(3) Pre-conditioning of the material to a particle size of a maximum of about 3:1, to be able to guarantee the detection and ejection through compressed air blast in an article-selective manner (Kranert, 2017).
(4) Separation of the fine grain fraction by upstream screening (Feil et al., 2021; Kranert, 2017).
(5) Regular cleaning of the sensors and the blow-out device (Feil et al., 2021; Kranert, 2017).
(6) Separation of two-dimensional components, such as films (Kranert, 2017).
(7) Compliance with the capacitive limits of the sorting plant, as overfilling can lead to disruptions in system operation (Feil et al., 2021).

3. Material and methods

This investigation examines the sensor-based plastic-type separation at the LWP sorting plant in Erftstadt. Based on a manual sorting analysis, the real-world sortability of different packaging designs is assessed and the causes of false ejections in SBS are discussed. Therefore, samples of all product streams of the plastic-type separation are analyzed. First, the product streams are sorted by material type (cf. Section 3.2.1). The PP, HD-PE, and PET bottle items sorted out in the first stage are then categorized by product type and design in the second sorting stage (cf. Section 3.2.2).

3.1. Sampling campaign

The sampling was conducted in October and November 2021. The plastic-type separation of the LWP sorting plant was defined as the balance sheet frame (system boundaries) for sampling (Fig. 1). Samples were taken from all product fractions of the plastic-type separation: PP, HD-PE, PET bottle, PS, PET tray, and mixed plastics hard (MP hard). Sampling was conducted before the final manual sorting in the LWP sorting plant to analyze the sorting quality of the NIR-VIS sorters and to exclude possible effects of the manual sorters.

The sampling campaign has been conducted according to Länderarbeitsgemeinschaft Abfall (LAGA) PN 98 (2023). The sample size comprises $n = 12$ samples per fraction. Four sampling containers with 90 L each were taken per sample. The material from two sampling containers each was mixed and a sample division was carried out so that one sample corresponded to about 180 L (resulting in an average sample mass of 6.2 kg [min: 4.0 kg, max: 9.1 kg], see Table S1 in Supplementary Materials).

To minimize the influence of various factors on the results, such as the origin and composition of the input, the loading of the bag opener, the condition of the plant, and the intervals between cleaning, three samples were taken per day, spread over four days, resulting in $n = 12$ samples per fraction. The planned times for the samples were 8.00 a.m., 10.00 a.m., and 12.00 noon. The samples for each time point were taken quickly one after the other and in the same order, such that the influencing factors for each time point are as constant as possible across all samples. Plant operation was to be influenced as little as possible by the sampling, which is why it was not always possible to adhere to the times. If there were time shifts, care was taken to maintain a time interval of about two hours between the individual samplings. Samples were taken on 10/29/2021, 11/02/2021, 11/18/2021, and 11/19/2021.

3.2. Manual sorting analysis

3.2.1. First sorting stage

In the first sorting stage, the samples were sorted manually by material type. For this purpose, a sorting catalog was created, which was initially orientated towards the product flows of the LWP sorting plant and supplemented by other fractions (Fig. 2a). The 12 samples per fraction were sorted and analyzed separately.

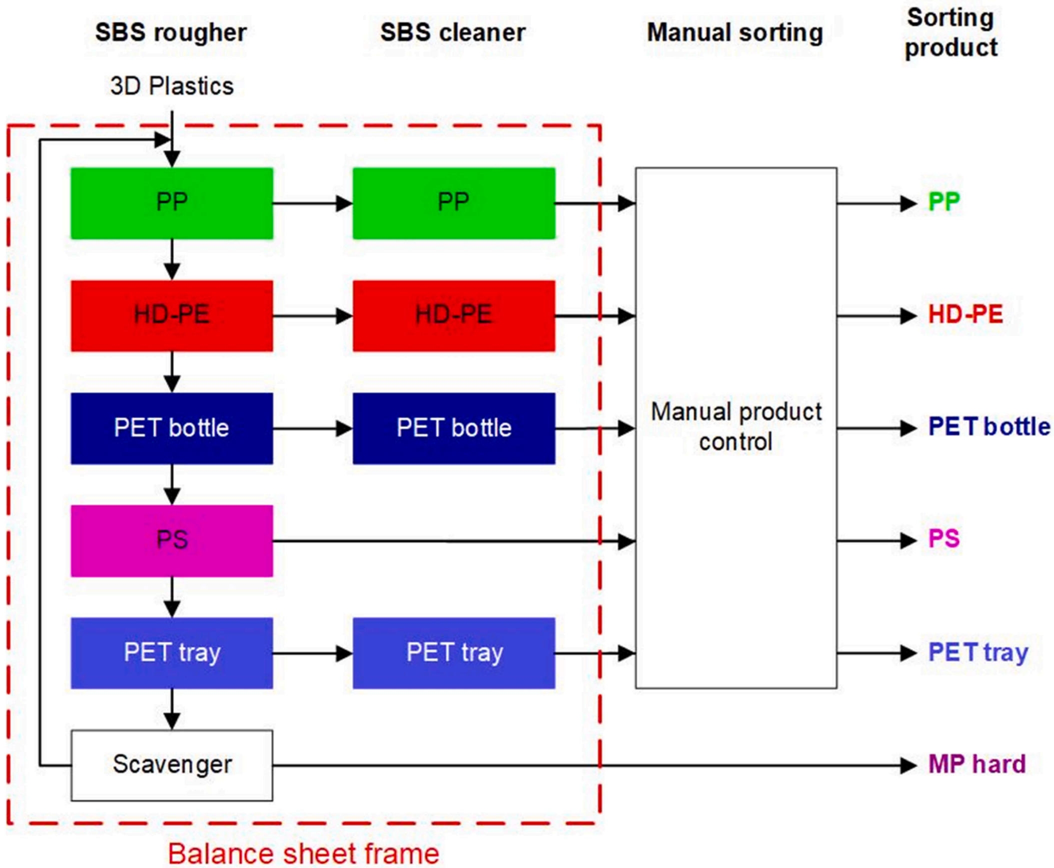

Fig. 1. Overview sampling campaign and sorting procedure.

Expanded polystyrene (EPS) was sorted as a separated fraction, as it is not suitable for recycling due to contamination. The ferrous and non-ferrous metals were combined into a metals fraction, assuming small quantities in the product streams of the plastic-type separation. Since carbon-black plastics (i.e., plastics that contain carbon-black as a coloring agent) cannot be detected by the NIR sorters, they were sorted separately.

The input of the plastic-type separation should ideally contain only dimensionally stable 3D articles (rigid plastic packages). Therefore, films were grouped as a separate fraction regardless of the material, and these were only plastic films. Since aluminum-vaporized plastics can be easily identified optically and are listed separately in the product specifications of Duales System Deutschland GmbH (DSD), they were sorted as a separate fraction, for example, the product specification of the sorting fraction *polypropylene plus* (Der Grüne Punkt - Duales System Deutschland GmbH, 2018a).

In addition, agglomerates and compounds were each defined as a separate fraction. Here, a distinction was made between *agglomerates* and *compounds* that were the same value as the recyclable material and those that were not. In the context of this paper, *compounds* are defined as different materials that were combined in the packaging design and were not separated by the consumer before disposal, such as plastic cups with paper wrapping. Foreign materials up to approx. 10 wt % were ignored and not classified as compounds. For example, bottles including lids, sleeves, or labels were considered bottles and not compounds.

Furthermore, trays including plastic film and, for example, yogurt cups with plastic sleeves were not classified as compounds, as the sleeves are plastic, and the films have a low mass proportion. Compounds of the same value are, for example, PS yogurt pots with a paper wrapping, if these were sorted into the PS product. If these were sorted into the PP product, for example, they would be compounds of different values because they do not contain any PP.

If two or more different materials or products were agglomerated by the consumer or during collection in the collection vehicle, they were counted as *agglomerates*. Up to approx. 10 wt % of foreign materials were ignored and not classified as agglomerates. In addition, packaging with more than approx. 25 vol % residual content was assigned to the agglomerates fraction.

Furthermore, silicone cartridges were sorted separately. According to the product specification of DSD of the PE sorting fraction, these must not be contained in the sorted product because they contain residues of silicone, which contaminate the material flow (Der Grüne Punkt – Duales System Deutschland GmbH et al., 2018b; Institut cyclos-HTP GmbH, 2021).

During the sorting of the first sorting stage, it was found that black plastics not colored with carbon black could be identified by the NIR sorters, hereinafter referred to as non-carbon black plastics (Ampacet Corporation, 2022; Henkel AG & Co. KGaA, 2019; Lifocolor Farben GmbH and Co et al., 2021). These were therefore assigned to the corresponding plastic type so that the carbon black plastics fraction (Fig. 2a) only includes those that cannot be identified by the NIR sorters.

3.2.2. Second sorting stage

As shown in Fig. 2b–e, a multistage sorting catalog was developed for the second sorting stage, in which PP, HD-PE, and PET bottle fractions of the first sorting stage were sorted in more detail. Both the correctly and incorrectly sorted items were analyzed. The sorting products of the 12 samples from the first sorting stage were mixed and analyzed together for each sorting fraction due to the low total mass of the corresponding subfractions (cf. Fig. 2e).

First, a distinction was made between packaging and non-packaging (Fig. 2b). Second, a distinction was made between food and non-food

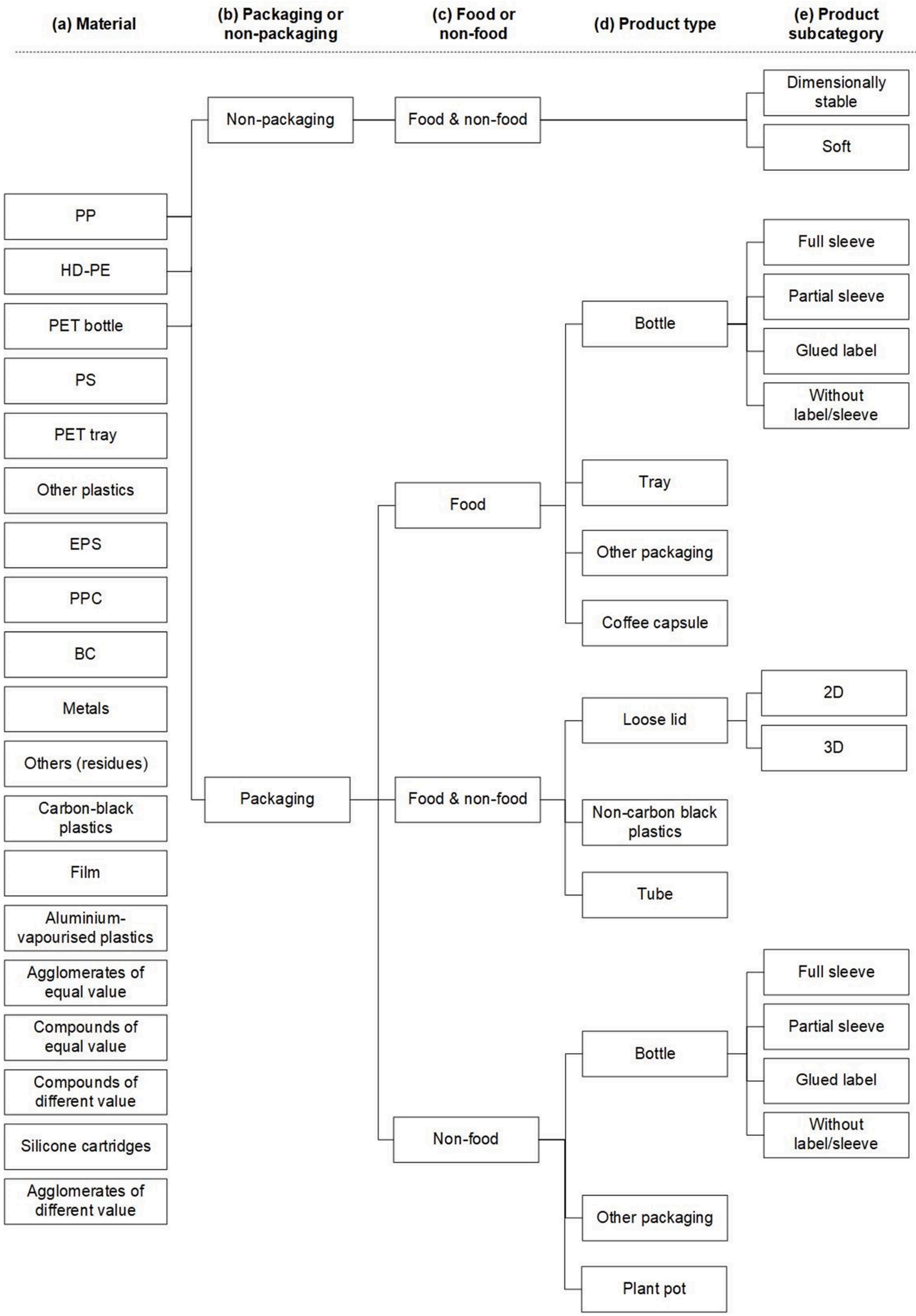

Fig. 2. Developed multi-stage sorting catalogue.

(Fig. 2c). Third, non-packaging was divided into the categories dimensionally stable and soft (Fig. 2e). No distinction was made here between food and non-food.

For food packaging, a distinction was made between bottles, trays, other packaging, and coffee capsules[2] (Fig. 2d). Non-food packaging includes bottles, other packaging, and plant pots. The bottles were subdivided into full sleeve, partial sleeve, glued label, and without label/sleeve (Fig. 2e). Furthermore, the product types loose 2D lids, loose 3D lids, non-carbon black plastics and tubes were introduced in the packaging sector (Fig. 2d). In these fractions, assuming low mass proportions and since it can be difficult to distinguish between loose food and non-food lids, for example, food and non-food packaging were sorted together.

Bottles with a sleeve content greater than approx. 80 % by area (a %) were classified as full-sleeve bottles. If the sleeve content was between approx. 5 a % and 80 a %, these were sorted as partial sleeve bottles. Bottles with a glued-on plastic or paper label were assigned to the product type bottle with a glued label. If the label or sleeve content was smaller than approx. 5 a %, the label or sleeve was neglected, and the bottle was assigned to the product type bottle without label/sleeve. Lids that were attached to the bottles were ignored in all cases.

Other packaging is all packaging that cannot be assigned to any of the other product types, for example, cups, trays, or buckets. Only loose lids are to be assigned to the fraction lids. Lids that were attached to bottles, bowls, or cans were ignored. Loose 2D lids are flat lids that have almost a 2D shape (see Fig. S1 in Supplementary Materials). Tubes were defined as tubes with a welded seam at the end of the tube. Products that are not LWP, such as toys or lunch boxes, are misdirected into the LWP waste and were therefore sorted separately as non-packaging.

If individual items or fragments of products could not be reliably assigned to the food or non-food category, they were declared as non-food. Items that could not be reliably identified as packaging were assigned to the non-packaging fraction. An overview of the sampling stages is shown in Fig. 2.

3.2.3. Mass balance and assessment

Based on the mass balance of the sorting plant, an average LWP input composition was determined for the sampling period. Using this composition and the results of the sorting analyses, an average composition for the input of the plastic-type separation was calculated. Based on this calculation, 15.9 wt % of the plant input is fed into the plastic-type separation. Assuming an annual input of 118,000 Mg/a into the sorting plant, this corresponds to 18,762 Mg/a input into the plastic-type separation. The determined composition serves as the basis for further calculations. The results of the sorting analyses were extrapolated to an annual input of 18,762 Mg/a into the plastic-type separation. The plastic type separation is used as the balance sheet framework for the calculation and the following results.

In the following, the composition of the input of the plastic-type separation as well as the composition of PP, HD-PE, and PET bottle by product type is presented. In addition, the yield (Y; share of correctly sorted articles) of the materials in the input of the plastic-type separation (see Eq. (1)) and the different product types per plastic grade are described. The yield is calculated based on the ratio of the mass flow of valuable materials contained in the target fraction ($\dot{m}_{i,\ \text{target fraction}}$) compared to the total amount of the respective valuable materials in the input of the plastic-type separation ($\dot{m}_{\text{valuables, input plastic type separation}}$).

$$Y_i = \frac{\dot{m}_{i,\ \text{target fraction}}}{\dot{m}_{\text{valuables, input plastic type separation}}} \tag{1}$$

[2] Although coffee capsules that are not completely empty are (in Germany) legally classified as non-packaging, they are described and evaluated in this paper in the same way as other packaging, as a high proportion of them must be sorted accordingly.

4. Results and discussion

4.1. Composition of material and packaging types

4.1.1. Composition input plastic-type separation

Based on the results of the sorting analysis of the first sorting stage, an average composition for the input of the plastic-type separation was determined (Fig. 3). Table S2 shows the results in more detail by displaying the confidence intervals using the 2.5 % percentile and the 97.5 % percentile.

With about 27.5 wt %, PP is the most common fraction, followed by PET bottles with about 17.3 wt %. HD-PE is represented with about 12.0 wt % and PET tray with about 11.8 wt %. Together with about 3.7 wt % PS, the pure plastic types account for a mass share of 72.3 wt % of the input in the plastic-type separation. Agglomerates of equal value are included with approx. 7.8 wt % and compounds of equal value with approx. 2.6 wt %. In addition, 1.7 wt% other plastics, 0.5 wt % EPS, and 0.4 wt % silicone cartridges are included.

Foreign materials that would ideally not enter the plastic-type separation, such as PPC, BC, metals, others (residues), carbon black plastics, film, aluminum-vaporized plastics, compounds of different values, and agglomerates of different values, make up a mass fraction of about 14.7 wt %, of which 9.7 wt % are films. If only the non-plastics PPC, BC, metals, others (residues), compounds of different values, and agglomerates of different values as well as the carbon black plastics are considered, they account for a mass share of about 3.7 wt %.

4.1.2. Composition of PP articles

Table 1 shows the composition of PP articles contained in the input of the plastic-type separation, classified by product type. With 51.1 wt %, more than half of the PP is allocated to the food category, compared to 25.9 wt % of non-food items. 23.0 wt % are allocated to the mixed category food and non-food.

The main application of PP in the packaging sector is other packaging, such as cups, trays, buckets, and cans. It includes 36.3 wt % other packaging food and 13.7 wt % other packaging non-food. This results in a total of 49.9 wt % of PP being other packaging. The third largest fraction of PP articles are trays with 12.8 wt %.

Only 9.9 wt % of the PP articles are bottles. Non-food bottles are represented with 8.2 wt %. At 7.3 wt % bottles with glued labels non-food, such as shampoo and detergent bottles, make up the largest share of PP bottles.

Plant pots (4.1 wt %) and plastic coffee capsules (0.3 wt %) are predominantly made of PP. Furthermore, lids are often made of PP. There are 7.8 wt % loose 2D lids and 1.9 wt % loose 3D lids included in the PP fraction. 11.7 wt % of the PP are non-packaging dimensionally stable.

4.1.3. Composition of HD-PE articles

In total, 69.0 wt % of the HD-PE articles are allocated to the category non-food, 18.1 wt % are allocated to the mixed category food and non-food, and only 12.9 wt % are allocated to the category food. 68.5 wt % of the HD-PE are bottles. Most of the bottles are bottles with a glued label (49.4 wt %). 9.0 wt % are bottles without a label/sleeve, 8.3 wt % are bottles with a full-sleeve and only 1.9 wt % are bottles with a partial sleeve.

The main area of application for HD-PE in the packaging sector is bottles with a glued label non-food (42.9 wt %), such as bottles for personal care products, detergents, and cleaning agents. The second largest product type is other packaging non-food with 13.2 wt %, which are mainly canisters. In addition, 8.7 wt % are non-packaging dimensionally stable. The products bottle with glued label food, bottle full sleeve non-food, bottle without label/sleeve non-food and tubes food & non-food are each represented with between 5.5 wt % and 6.5 wt %. The composition of HD-PE by product type is shown in Table 1.

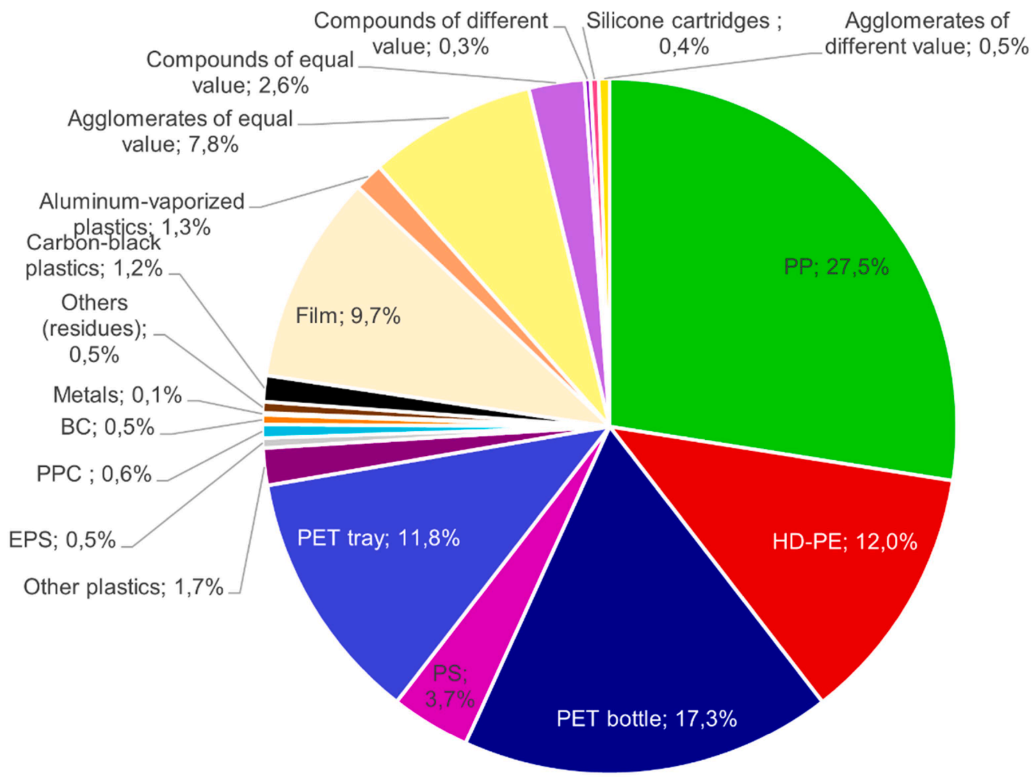

Fig. 3. Composition of the input of the plastic type separation in weight percent [wt %].

Table 1
Composition of PP, HD-PE, and PET bottle fractions [wt %].

Product type / Product material	PP	HD-PE	PET bottle
Bottle full-sleeve food	0.5 %	2.1 %	11.7 %
Bottle partial sleeve food	–	1.3 %	25.2 %
Bottle glued label food	0.5 %	6.5 %	11.1 %
Bottle without label/sleeve food	0.7 %	2.8 %	9.5 %
Bottle full sleeve non-food	0.2 %	6.1 %	4.0 %
Bottle partial sleeve non-food	0.1 %	0.6 %	8.4 %
Bottle glued label non-food	7.3 %	42.9 %	23.6 %
Bottle without label/sleeve non-food	0.5 %	6.2 %	2.4 %
Tray food	12.8 %	–	–
Other packaging food	36.3 %	0.2 %	2.6 %
Coffee capsule food	0.3 %	–	–
Loose 2D lid food & non-food	7.8 %	0.4 %	–
Loose 3D lid food & non-food	1.9 %	0.5 %	–
Non-carbon black plastics food & non-food	0.3 %	1.7 %	0.3 %
Tube food & non-food	0.1 %	5.5 %	–
Other packaging non-food	13.7 %	13.2 %	0.9 %
Plant pot non-food	4.1 %	–	–
Non-packaging dimensionally stable food & non-food	11.7 %	8.7 %	0.4 %
Non-packaging soft food & non-food	1.2 %	1.3 %	–

4.1.4. Composition of PET bottle articles

60.0 wt % of the PET bottle fraction was assigned to the food category and 39.3 wt % to the non-food category. 0.3 wt % are non-carbon black PET bottles food & non-food. In addition, 0.4 wt % are non-packaging dimensionally stable, such as reusable beverage bottles. It should be noted that there is a deposit return system for PET beverage bottles in Germany. The PET bottles contained in the LWP are therefore PET bottles for other applications such as ketchup or cleaning agents.

The PET bottles contain a total of 95.8 wt % packaging bottles. At 34.7 wt %, most PET bottles have a glued label, followed by 33.5 wt % bottles with a partial sleeve. Only 15.7 wt % are bottles with a full-sleeve. At 11.9 wt %, the fewest bottles are without a label/sleeve. The composition of PET bottles by product type is shown in Table 1.

4.1.5. Comparison of the composition of PP, HD-PE, and PET bottle

When comparing the three materials PP, HD-PE, and PET bottle, it is observed that PP (51.1 wt %) and PET bottle (60.0 wt %) are predominantly used in the food sector. HD-PE (69.0 wt %), on the other hand, is mainly used in the non-food sector. PP is used by 49.9 wt % for other packaging and only 9.9 wt % for bottles. In contrast, 68.5 wt % of HD-PE is used to produce bottles, and 13.4 wt % for other packaging.

4.2. Sortability with SBS

4.2.1. Yield of materials that enter the plastic-type separation

Table 2 summarizes the results of the first sorting stage as a confusion matrix using mean values. Table S3 shows the results in more detail by displaying the deviations using the 2.5 % percentile and the 97.5 % percentile.

PP has the highest yield, with 94.4 wt %. With 89.2 wt %, the second-highest yield is for PS, followed by PET tray with 85.5 wt % and HD-PE with 83.1 wt %. With 73.6 wt % yield, the sorting result for PET bottle is poor.[3] Other plastics are correctly sorted at 64.4 wt %. The plastic types PP, HD-PE, PET-bottle, and PS are sorted into the MP hard with between 4.9 wt % and 14.8 wt % yield.

The different yields of the plastic types are most likely caused by a combination of operational influences (e.g., material flow composition and occupation density per SBS unit [Kroell et al., 2024]) and material-specific product designs. Regarding the influence of material-specific packaging designs, it can be noted that PP articles are rarely combined with other materials and are frequently printed. Similarly, despite paper wrappings (which are assigned to the category of composites of equal value), PS articles are rarely combined with other materials, which could thus explain the high yield of PP and PS.

[3] In the context of this paper, sorting results are described as follows: ≥ 95 %: "very good"; 95 % – 90 %: "good"; 75% – 50 %: "poorly"; < 50 %: "very poorly".

Table 2
Yield of materials that enter the plastic-type separation [wt %].

Product type / Output fraction	PP	HD-PE	PET bottle	PS	PET tray	MP hard
PP	**94.4 %**	0.2 %	0.2 %	0.1 %	0.2 %	4.9 %
HD-PE	0.6 %	**83.1 %**	0.1 %	0.3 %	1.2 %	14.8 %
PET bottle	3.5 %	0.1 %	**73.6 %**	0.7 %	8.0 %	14.1 %
PS	1.2 %	0.2 %	0.7 %	**89.2 %**	0.4 %	8.3 %
PET tray	1.7 %	0.2 %	9.8 %	0.9 %	**85.5 %**	1.9 %
Other plastics	5.0 %	15.2 %	9.4 %	3.1 %	2.9 %	**64.4 %**
EPS	1.4 %	0.5 %	5.2 %	4.3 %	1.3 %	87.3 %
PPC	12.5 %	0.5 %	26.1 %	0.6 %	5.7 %	54.6 %
BC	0.0 %	0.7 %	0.4 %	0.2 %	10.3 %	88.4 %
Metals	30.5 %	1.1 %	10.5 %	1.4 %	0.3 %	56.3 %
Others (residues)	25.5 %	0.5 %	21.5 %	1.0 %	15.7 %	35.8 %
Carbon black plastics	8.8 %	1.7 %	7.0 %	0.2 %	5.0 %	77.3 %
Film	25.4 %	6.7 %	0.5 %	1.9 %	3.3 %	62.1 %
Aluminum-vaporized plastics	51.2 %	0.3 %	3.2 %	0.7 %	6.3 %	38.2 %
Agglomerates of equal value	31.3 %	0.4 %	0.9 %	4.8 %	26.2 %	36.5 %
Compounds of equal value	37.6 %	2.6 %	0.0 %	9.8 %	28.9 %	21.2 %
Compounds of different value	12.6 %	4.7 %	70.2 %	1.5 %	7.8 %	3.3 %
Silicone cartridges	0.0 %	67.7 %	0.0 %	0.0 %	0.0 %	32.3 %
Agglomerates of different value	6.1 %	6.6 %	66.4 %	3.4 %	17.5 %	0.0 %

In contrast, HD-PE or PET bottles are often combined with sleeves or labels made from different materials, which can make the SBS classification more difficult and thus explain the lower yields. Additionally, the German LWP contains HD-PE bottles with a metallic gloss that results in an unspecific NIR reflection. Therefore, HD-PE bottles with a metallic gloss are therefore difficult to be correctly classified and sorted (Fig. S8). Further, it should be noted that no distinction is made between opaque and clear PET bottles in the manual sorting process. As opaque PET bottles without full sleeves are to be sorted into the MP hard by the NIR sorters, this leads to a deterioration in the yield shown for PET bottles.

All other materials contained in the input of the plastic-type separation, which cannot be assigned to any of the recoverable plastic types PP, HD-PE, PET bottle, PS, and PET tray are to be sorted into the MP hard. With more than 77.0 wt % yield into the MP hard, there is a good sorting result for EPS, BC, metals, and carbon black plastics. Aluminum-vaporized plastics are sorted into the PP at 51.2 wt % due to aluminum-vaporized films that are sorted into the PP, as up to 10.0 wt % films may be contained in the PP product (Der Grüne Punkt - Duales System Deutschland GmbH, 2018a).

Regarding operational influences, it can be seen, for example, that the false ejections are influenced by the SBS cascade design, i.e., the order in which the different polymers are to be sorted. For example, false-ejections of HD-PE in the PP product with 0.6 wt % are three times more likely than false ejections of PP in the HD-PE product, as PP is sorted before HD-PE in the investigated SBS cascade (cf. Fig. 1).

4.2.2. *Yield of different types of plastic bottles*

The first half of Table 3 summarizes the influence of the product design of different bottles based on the sorting results of the different bottle categories and materials. Bottles without label/sleeve non-food have the best yield with an average of 91.5 wt % across all materials. Bottles with glued label non-food and bottles with partial sleeve food are correctly sorted at 87.8 wt % and 87.4 wt % yield, respectively. Bottles with a glued label food and bottles without a label/sleeve food are sorted at 83.7 wt % and 82.8 wt %. Bottles with partial sleeves non-food are correctly sorted at an average of 78.7 wt %. The worst sorting result across all materials is for bottles full sleeve food with 65.9 wt % yield, followed by bottles full sleeve non-food with 72.1 wt %.

PET bottles partial sleeve non-food are sorted very poorly with only 39.7 wt % correct output. This is most likely due to the large surface area of the sleeves of fabric softener bottles and poor detection of areas where the sleeve is loose (see Fig. S2). If the sleeve does not fit tightly, the sleeve is detected first and foremost, and the bottle can hardly or not at all be detected. On the other hand, partial sleeve food bottles often have a smaller sleeve so that the bottles can be detected better. This is reflected in the yield of 80.1 wt % yield of PET bottles partial sleeve food. In addition, the PET bottle partial sleeve non-food category contains shiny fabric softener bottles that are to be sorted into the MP hard category. These were not recorded separately in the second sorting stage and can therefore not be deducted from the results.

Table 3
Yield of different product types [wt %].

Product type	Product material			
	PP	HD-PE	PET bottle	Average
Bottle full-sleeve food	80.5 %	43.3 %	73.9 %	65.9 %
Bottle partial sleeve food	–	94.8 %	80.1 %	87.4 %
Bottle glued label food	100.0 %	75.2 %	75.9 %	83.7 %
Bottle without label/sleeve food	100.0 %	64.6 %	83.9 %	82.8 %
Bottle full sleeve non-food	72.3 %	77.7 %	66.2 %	72.1 %
Bottle partial sleeve non-food	100.0 %	96.3 %	39.7 %	78.7 %
Bottle glued label non-food	97.4 %	92.6 %	73.5 %	87.8 %
Bottle without Label/Sleeve non-food	98.1 %	93.2 %	83.3 %	91.5 %
Tray food	98.7 %	–	–	98.7 %
Other packaging food	97.9 %	62.9 %	74.5 %	78.4 %
Coffee capsule food	68.4 %	–	–	68.4 %
Loose 2D lid food & non-food	99.2 %	88.6 %	–	93.9 %
Loose 3D lid food & non-food	65.1 %	61.5 %	–	63.3 %
Non-carbon black plastics food & non-food	62.6 %	83.1 %	67.5 %	71.1 %
Tube food & non-food	82.7 %	53.2 %	–	67.9 %
Other packaging non-food	95.6 %	78.4 %	43.1 %	72.4 %
Plant pot non-food	87.8 %	–	–	87.8 %
Non-packaging dimensionally stable food & non-food	80.1 %	80.4 %	100.0 %	86.8 %
Non-packaging soft food & non-food	98.3 %	55.3 %	–	76.8 %

Furthermore, HD-PE bottles full sleeve food are sorted very poorly with only 43.3 wt % yield. This is due to bottles of the “Fresubin” brand, which are similar designed to the bottles of the “Viss” brand, which are bottles full sleeve non-food (see Fig. S3 and Fig. S4). These bottles have a PET sleeve such that the NIR sorters need to assign a mixed spectrum of HD-PE bottle and PET sleeve correctly (Chen et al., 2023a). The yield of 64.6 wt % for HD-PE bottles without label/sleeve food is due to mayonnaise bottles of the “Luvat” brand (see Fig. S5). Those bottles often still contain residual contents, which can influence the NIR spectrum so much that the bottle is no longer detected correctly. In addition, residual contents lead to a higher weight of the bottles, so the compressed air blast may be too weak to eject the bottle over the separating apex in the case of high residual contents.

The best sorting result is 100.0 wt % correct output for PP bottles with glued label food, PP bottles without label/sleeve food, and PP bottles with partial sleeve non-food. It must be considered that the results are based on the materials contained in the samples and that false outputs can occur with an infinitely large sample quantity. Partial sleeve food bottles were not included in the samples of the PP sorting product.

Irrespective of whether the bottles are food or non-food, a mean value calculation shows that 87.2 wt % of bottles without label/sleeve are correctly sorted out, followed by bottles with a glued label (85.8 wt %), bottles with partial sleeves (82.2 wt %) and full sleeve bottles (69.0 wt %). When comparing bottles with labels or sleeves to bottles without labels/sleeves, it becomes clear that bottles without labels/sleeves result in the highest yield. In relation to bottles without labels/sleeves, bottles with full sleeves are sorted about 20.9 % worse, bottles with partial sleeves are sorted about 5.7 % worse, and bottles with glued labels are sorted 1.6 % worse. In summary, the analysis of various bottles shows that the smaller and tighter the sleeve, the better the bottle recognition.

4.2.3. *Yield of other product types per plastic type*

The yields of all other product types distinguished in the second sorting stage are compared in the second half of Table 3. Trays, coffee capsules, and plant pots contained in the samples were exclusively made of PP. It should be noted that these products can also be made from other materials, such as PE or PS. With 98.7 wt % yield, the sorting result for trays is very good. Coffee capsules are correctly sorted by 68.4 wt %. The reason for this is that the back of the coffee capsules is better detected compared to the front (see Fig. S6). The coffee capsules usually have a foil-like lid made of aluminum or plastic. Because of the distance between the foil and the capsule, the NIR radiation is not sufficient to reach the PP capsule and recognize it. The proportion of false rejects is therefore due to the position of the coffee capsules on the conveyor belt. In addition, similar to round lids, they can perform relative movements on the conveyor belt if they hit the belt borders.

In the area of other packaging, clear differences can be seen in the yield. Other packaging made of PP is sorted very good at 97.9 wt % (food) and 95.6 wt % (non-food). In contrast, only 74.5 wt % (food) and 43.1 wt % (non-food) of other PET packaging is correctly sorted. It is important to note that other packaging made of PET is contained in LWP in a significantly lower amount compared to PP (cf. Table 1). Therefore, individual packages design of other packaging in PET have a stronger influence on the overall yield of other packaging compared to PP.

Further, loose 2D lids are sorted better with an average of 93.9 wt % yield than loose 3D lids, which are correctly sorted at an average of 63.3 wt % yield. As a result, loose 3D lids are sorted about 32.6 % worse than loose 2D lids. The cause of this is probably due to a relative movement of the loose 3D lids on the conveyor belt. The loose 3D lids are predominantly round lids, which can perform a relative movement depending on their position on the conveyor belt. The loose HD-PE 2D lids are also often round. In contrast, the loose PP 2D lids contain round lids as well as square or oval lids, which are very flat and can therefore perform fewer relative movements on the conveyor belt. The different shapes of PP and HD-PE 2D lids could lead to loose PP 2D lids having a higher yield. It can be assumed that some of the loose lids contained in the plant input are already sorted out before entering the plastic-type separation. Since some of the loose lids are small, they can be screened into the fine material (see Section 2.1). In addition, it can be assumed that especially loose round 3D lids are incorrectly ejected at the plastic NIR sorter due to relative movement on the conveyor belt and are not fed to the plastic type separation.

On average, only 71.1 wt % of non-carbon black plastics are correctly sorted. This shows that some dark materials, even if they are colored without carbon black, are still poorly sorted. Further, the yield differs between different polymers due to polymer-specific product designs. For example, non-carbon black PP and PET are sorted correctly to 62.6 wt % and 67.5 wt % correct, respectively. In contrast, non-carbon black HD-PE is sorted with 83.1 wt % yield, which could be caused by non-carbon black HD-PE detergent bottles of the "Perwoll" brand, which can be sorted very well (see Fig. S7).

PP tubes are sorted with 82.7 wt % yield. It must be considered here that PP tubes were included in the samples in very small numbers and the results are associated with a statistical uncertainty. HD-PE tubes are sorted at 53.2 wt % yield. This sorting result is because tubes can be made from HD-PE and LD-PE. Since the HD-PE sorter should only sort out HD-PE and differentiation between HD-PE and LD-PE is complex, this often results in false rejects.

In the area of non-packaging, clear differences can be seen in the yield. Non-packaging dimensionally stable made of PP and HD-PE show similar yield with 80.1 wt % and 80.4 wt % yield. In contrast, 100.0 wt % of non-packaging dimensionally stable made of PET is correctly sorted. It must be considered that the result is based on the products contained in the samples and that false ejections can occur with an infinitely large number of products. 98.3 wt % of non-packaging soft made of PP is correctly sorted, whereas only 55.3 wt % made of HD-PE is correctly sorted. Since the fractions of non-packaging can contain a large variety of products, it is often (currently) not possible to include NIR reference spectra of all products into the NIR classifiers to avoid these false rejects completely.

4.3. Validation of the minimum standard for packaging design

Based on the results from Sections 4.1 and 4.2, guidelines for a sorting and/or recycling-friendly packaging design such as the minimum standard for packaging design (Stiftung Zentrale Stelle Verpackungsregister, 2023) can be compared with our results on the real-world sortability of post-consumer plastic packaging in the plastic type separation in LWP sorting plants (RQ 3).

4.3.1. Sleeves and labels

The minimum standard for packaging design states that applying labels with foreign material over a large area (> 50 a %) or full-sleeve labeling can have a negative impact on the sensor-based sortability and therefore requires a case-by-case assessment (Stiftung Zentrale Stelle Verpackungsregister, 2023). Our findings confirm this statement under real-world sorting plant conditions, as we have shown that the correct sorting of plastic decreases with increasing sleeve area from 87.2 wt % for unlabeled/-sleeved bottles to 69.0 wt % for full-sleeved bottles (Section 4.2.2). As discussed in Section 4.1 (Table 1), about 87 wt %[4] of all plastic bottles contain labels or sleeves and between 7 wt % (PP) to 16 wt % (PET) of all plastic bottles are full-sleeved. Thus, a significant room for improved sortability is given around sleeved bottle designs.

Based on our results, if sleeve are used, it is recommended that they should cover as small of an area of the bottle as possible and should be applied as close-fitting as possible. Further, sleeves should be designed in such a way that the NIR sensors can detect the bottle below the sleeve, i.e., the sleeve should neither be black on the inside nor aluminum-vaporized (cf. Chen et al., 2023a). From a sorting perspective, ideally, the sleeve should be made of the same material as the bottle, however, different requirements might exist from a recycling perspective.

4.3.2. Composites

The minimum standard for packaging design states that packages made of different polymer types on the front and back side of the packaging require a case-by-case assessment (Stiftung Zentrale Stelle Verpackungsregister, 2023). This corresponds with our findings, as we have shown that composites result in significantly lower yields (Section 4.2.1). For example, it was shown that only 68.4 wt % of coffee capsules are sorted correctly due to different materials on the front and back side of the packaging (cf. Section 4.2.3).

Based on our results, it is therefore recommended, to avoid composites or to design them in such a way that the individual components are automatically separated from each other when the product is used. If this is not possible, the individual components should be easily detached from each other. Composites should bear a notice for the consumer that the components should be separated from each other and disposed of separately into the corresponding waste stream.

4.3.3. Color

The minimum standard for packaging design states that coloring using carbon-black pigments and metal pigments (> 50 a %) require a case-by-case assessment (Stiftung Zentrale Stelle Verpackungsregister, 2023). While carbon-black polymers cannot be sorted by plastic type using NIR spectroscopy (cf. Section 2.2.2) and thus already lead to material losses before the plastic type separation in the investigated LWP sorting plant (cf. Sections 2.1 and 3.1), our study validates the influence of color on the real-world sensor-based sortability. First, it was shown that glossy and highly reflective colors (e.g., induced by metal pigments) results in a non-specific reflection of the NIR radiation and lead to false ejections. Second, it was shown that besides carbon black, dark colors

[4] Macro-average over the material classes PP, HD-PE, and PET bottle (cf. Table 1)

should be avoided in general as it was shown that non-carbon black plastics are sorted correctly at only 71.1 wt % and thus worse than other colors (cf. Section 4.2.3). Furthermore, to enable high-quality recycling, products should be produced that are as transparent as possible; this is particularly important in PET bottle recycling. The focus of PET bottle recycling is currently on transparent bottles, so there are no recycling options for opaque PET bottles (Institut cyclos-HTP GmbH, 2021; Pitschke and Kreibe, 2020).

4.3.4. Shape

An additional aspect that has become apparent in our investigations is the packaging shape. It was shown that rolling packaging (i.e., packaging that tends to roll on fast-moving acceleration belt due to their, e.g., round or cylindrical geometry) results in considerably lower yields compared to less rolling packaging due to relative movements on the acceleration belt of SBS units. For example, a comparison between 2D and 3D shaped lids (Section 4.2.3) showed that round 3D lids are sorted about 32.6 wt % worse than loose flat 2D lids. Therefore, it could be important to consider also the packaging shape in the sortability assessment.

4.4. Estimate for improvement potentials

To estimate what additional potential of recyclable materials could result from better sortable plastic packaging designs (RQ 4), we extrapolated our results to the 2.92 million Mg/a of LWP in total in Germany (cf. Section 1.1). Here, the simplified assumption was made that the results of this investigation can be transferred to all other 38 LWP sorting plants in Germany to give a first estimate on the improvement potential despite the limited data availability (cf. Section 1.2). Further, these potentials only address the plastic-type separation and valuable plastics mis-sorted into other product fractions such as BC or PPC or the sorting residues are not considered. Regarding plastic type separation, these estimates represent a theoretical maximum due to the inherently technically limited efficiency of SBS units (cf. Kroell et al., 2024). Composites and agglomerates of equal value as well as carbon black plastics and films are not included in this estimation.

The results of the extrapolation show that, under the above assumptions, about 48,300 Mg/a[5] (95 % confidence interval [CI]: 25,900 Mg/a – 78,500 Mg/a) of valuable 3D plastics, such as PP, HD-PE, PET bottles, PS, and PET trays, are estimated to be incorrectly sorted annually in Germany. About 28,800 Mg/a (95 % CI: 20,100 Mg/a – 44,100 Mg/a) of these plastics are estimated to be sorted into the MP hard (mixed plastics) and are estimated to be (currently) fully sent for energy recovery instead of recycling. The remaining about 19,500 Mg/a (95 % CI: 5,800 Mg/a – 34,400 Mg/a) of valuable plastics are estimated to be mis-sorted into other plastic fractions. Depending on the downstream recycling process, these can be partially recovered. A total of about 287,000 Mg/a (95 % CI: 271,300 Mg/a – 301,300 Mg/a) of the above plastics are estimated to be correctly sorted in LWP plastic type separations. Through better sorting results in the plastic type separation alone, the amount of the above plastics could be theoretically increased by about 16.8 % to 335,300 Mg/a (95 % CI: 297,200 Mg/a – 379,800 Mg/a) pure 3D plastics PP, HD-PE, PET bottle, PS, and PET tray, when not considering material losses prior to the plastic type separation.

5. Conclusions

Since LWP represents the largest post-consumer plastic waste material flow, the correct sorting in LWP sorting plants is crucial for the overall material circulation. Packaging design and the applied sorting technology influence the correct sorting strongly. As current assessments often focus only on a theoretical assessment of the recyclability of individual plastic packaging, this publication aimed to quantify the real-world sortability of post-consumer plastic packaging in LWP sorting plants. Furthermore, the proportions of PP, HD-PE, and PET bottles by packaging type are analyzed. Therefore, the sensor-based plastic-type separation at the LWP sorting plant in Erftstadt was investigated based on a manual sorting analysis. The sorting analysis can be divided into two main sorting steps: (1) sorting by materials and (2) sorting by product type and design.

The three most common polymers in the input of the plastic-type separation are PP (27.5 wt %), PET bottle (17.3 wt %), and HD-PE (12.0 wt %). PP contains 51.1 wt % food packaging. Most PP packaging can be assigned to the category of other packaging (49.9 wt %), such as cups and buckets. HD-PE contains 31.0 wt % food packaging. Most HD-PE packages are bottles (68.5 wt %), of which most bottles are bottles with glued labels (72.0 wt %). PET bottle contains 60.0 wt % food packaging. Most PET bottles contain glued labels (34.7 wt %) or partial sleeves (33.5 wt %). Only 11.9 wt % of PET bottles are bottles without labels/sleeves. [RQ1]

In terms of the valuable polymer fractions sorted out in the plastic-type separation, PP (94.4 wt %) showed the highest yield, followed by PS (89.2 wt %), PET tray (85.5 wt %), HD-PE (83.1 wt %), and PET bottles (73.6 wt %). Across all investigated polymers, the yield decreased with increasing sleeve or label coverage. For example, average yields decreased by 20.9 % when comparing plastic bottles without labels/sleeves (87.2 wt %) with full-sleeved plastic bottles (69.0 wt %).

Further, composite materials are sorted more poorly than pure materials. This is clearly illustrated by the example of coffee capsules (68.4 wt % yield). The back of the coffee capsules, which is often made of PP, can be detected well, whereas the front, which is often made of aluminum or plastic film and is contaminated with coffee residues, is poorly detected.

In addition, the sorting results were also influenced by the packaging color and shape. Non-carbon black bottles were correctly sorted by only 71.1 wt %. Rolling material results in relative movement on the SBS acceleration belt and thus decreased yield. For example, the yield was reduced by 32.6 %, when comparing non-rolling loose 2D lids (93.9 wt %) with rolling loose 3D lids (63.3 wt %). [RQ2]

Many of the sorting errors could be attributed to packaging design that was, SBS's point of view, not optimal. A comparison with specifications for sorting and/or recycling-friendly packaging design, such as the minimum standard for packaging design (Stiftung Zentrale Stelle Verpackungsregister, 2023), showed that the influence of sleeves and labels, material composites and colors are considered in the specifications. However, the packaging shape has so far received less consideration and based on our results, should also be included in the future as an additional criterion for assessing the (sensor-based) sortability. [RQ 3]

Assuming that the results can be extrapolated to Germany, we have shown that optimal sorting results at the sensor-based plastic separation level alone could lead to up to 48,300 Mg/a (95 % CI: 25,900 Mg/a – 78,500 Mg/a) of additionally recovered pure plastics. This theoretical potential results from up to 28,800 Mg/a (95 % CI: 20,100 Mg/a – 44,100 Mg/a) of valuable plastics, such as PP, HD-PE, PET bottles, PET trays and PS, which are currently mis-sorted into the MP hard fraction and 19,500 Mg/a (95 % CI: 5800 Mg/a – 34,400 Mg/a) of valuable plastics that are mis-sorted into other plastic sorting product streams (e.g., PP packaging in HD-PE pre-concentrates). [RQ 4]

In future research, our investigations should be extended to the full LWP sorting plant, such that, e.g., false ejection into the sorting residues or false ejection of other materials, such as PPC or BC in the pre-conditioning stage could be considered. Furthermore, it is vital to compare our results with other LWP sorting plants due to the influence of, e.g., different sorting equipment, process designs, and input materials. Furthermore, it could be analyzed how the sorting results are

[5] Results in Section 4.4 are rounded to multiples of 100 Mg/a to reflect the high uncertainty of the extrapolation due to the extrapolation from one LWP sorting plant to all LWP sorting plants in Germany.

influenced by different SBS settings and how the product design and the sorting programs of the SBS could be better aligned. Samples could be analyzed before and after optimizing the sorting programs to determine to what extent it is sufficient to adjust the sorting program and for which product types this is not sufficient, and the product design needs to be adjusted.

Ultimately, our research highlights the potential of an improved alignment between product design and sorting technology for an increased real-world sortability of LWP. By ensuring a good real-world sortability of packaging items through a sorting-friendly packaging design as well as a further technical development of today's sorting technology, more and purer plastic pre-concentrates can be sorted towards the respective recycling path, ultimately resulting in higher recyclate qualities and quantities and higher environmental benefits through enhanced primary plastic substitution.

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CRediT authorship contribution statement

Michelle Jakobs: Writing – original draft, Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nils Kroell:** Writing – original draft, Writing – review & editing, Visualization, Validation, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Michelle Jakobs conducted the research presented in this paper as part of her master's thesis at the Department of Anthropogenic Material Cycles at RWTH Aachen University, carried out externally at the REMONDIS GmbH & Co. KG's LWP sorting plant in Erftstadt. Following the completion of her master's thesis, Michelle Jakobs took up a position as a (Deputy) Operations Manager at the investigated LWP sorting plant in Erftstadt. The current paper is based on the results of Michelle Jakobs master thesis, but the corresponding peer-reviewed article was written during her tenure at REMONDIS GmbH & Co. KG. Nils Kroell declares no potential conflicts of interest concerning the research, authorship, and/or publication of this article.

Data availability

The data that has been used is confidential.

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Supplementary materials

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References

Ampacet Corporation, 2022. Near infrared sorting for recycling black packaging. https://www.ampacet.com/masterbatch-products/core-product/rec-nir-black, [accessed 17.03.22].

Bachmann, M., Zibunas, C., Hartmann, J., Tulus, V., Suh, S., Guillén-Gosálbez, G., Bardow, A., 2023. Towards circular plastics within planetary boundaries. Nat. Sustain. https://doi.org/10.1038/s41893-022-01054-9.

Bifa. Recyclingfähigkeit von Verpackungen, 2019. https://www.interzero.de/fileadmin/Verpackungsoptimierung/530592_Recyclingfaehi, keit_Bewertungskatalog_v6_3_Download.pdf [accessed 11.08.23].

Bilitewski, B., Härdtle, G., 2013. Abfallwirtschaft: Handbuch für Praxis Und Lehre. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-79531-5.

Bünemann, A., Rachut, G., Christiani, J., Langen, M., Wolters, J., 2011. Planspiel Zur Fortentwicklung der Verpackungsverordnung. Umweltbundesamt, Dessau-Roßlau.

Chen, X., Kroell, N., Althaus, M., Pretz, T., Pomberger, R., Greiff, K., 2023a. Enabling mechanical recycling of plastic bottles with shrink sleeves. Resour. Conserv. Recycl. https://doi.org/10.1016/j.resconrec.2022.106719.

Chen, X., Kroell, N., Feil, A., Greiff, K., 2023b. Sensor-based sorting. Eds.. In: Meskers, C., Worrell, E., Reuter, M.A. (Eds.), Handbook of Recycling: State-of-the-art for Practitioners. Analysts, and Scientists (2nd ed.)ISBN 9780323855143.

Cudjoe, D., Zhu, B., Nketiah, E., Wang, H., Chen, W., Qianqian, Y., 2021. The potential energy and environmental benefits of global recyclable resources. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2021.149258.

cyclos HTP, 2023. Anforderungs- und Bewertungskatalog Version 5.1. https://www.cycloshtp.de/publikationen/a-b-katalog, [accessed 11.08.23].

Dehoust, G., Christiani, J., 2012. Analyse und Fortentwicklung der Verwertungsquoten für Wertstoffe.

Dehoust, G., Hermann, A., Christiani, J., Bartnik, S., Beckamp, S., Bünemann, A., 2021 Ermittlung der Praxis der Sortierung und Verwertung von Verpackungen. Umweltbundesamt. Öko-Institut e.V. Dessau Roßlau.

Der Grüne Punkt - Duales System Deutschland GmbH, 2018a. Produktspezifikation 03/2018 Fraktions-Nr. 324-1: sortierfraktion: polypropylen plus.

Der Grüne Punkt – Duales System Deutschland GmbH, 2018b. Produktspezifikation 03/2018 Fraktions-Nr. 329: Sortierfraktion: Polyethylen.

Der Grüne Punkt - Duales System Deutschland GmbH, 2023. Recyclingfähigkeit von Verpackungen ermitteln mit dem RecyclingCOMPASS. https://www.gruener-punkt.de/de/politik-gesellschaft/mediathek/informationsmaterial. [accessed 11.08.23].

DIN EN ISO 14021, 2021. Umweltkennzeichnungen und -deklarationen. Deutsches Institut für Normung e. V. Beuth Verlag; Berlin.

Feil, A., Kroell, N., Pretz, T., Greiff, K., 2021. Anforderungen an eine effiziente technologische Behandlung von Post-Consumer Verpackungsmaterialien. Müll und Abfall 7/2021. https://doi.org/10.37307/j.1863-9763.2021.07.04.

Hahladakis, J., Iacovidou, E., 2018. Closing the loop on plastic packaging materials. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2018.02.330.

Hahladakis, J., Iacovidou, E., 2019. An overview of the challenges and trade-offs in closing the loop of post-consumer plastic waste. J. Hazard. Mater. https://doi.org/10.1016/j.jhazmat.2019.120887.

Henkel AG & Co. KGaA, 2019. Henkel führt recycelbare schwarze Plastikverpackung ein. https://www.henkel.de/resource/blob/937142/f70345e1a390370437b99e6ef0cba95c, data/2019-05-03-henkel-presseinformation-schwarze-recycelbare-verpackungen.pdf.

Institut cyclos-HTP GmbH, 2021. Prüfung und Testierung der Recyclingfähigkeit: anforderungs- und Bewertungskatalog des Institutes cyclos-http zur EU-weiten Zertifizierung CHI Standard.

INTERSEROH Dienstleistungs GmbH, 2022. Leichtverpackungen: high-Tech Sortierdienstleistungen. https://www.interseroh.de/leistungen/recycling/sortierdienstleistungen, [accessed 05.10.23].

Knappe, F., Reinhardt, J., Kauertz, B., Oetjen-Dehne, R., Buschow, N., Ritthoff, M., Wilts, H., Lehmann, M., 2021. Technische Potenzialanalyse zur Steigerung des Kunststoffrecyclings. Umweltbundesamt ifeu.

Kranert, M., 2017. Einführung in Die Kreislaufwirtschaft. Springer, Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-8348-2257-4.

Kroell, N., Chen, X., Greiff, K., Feil, A., 2022a. Optical sensors and machine learning algorithms in sensor-based material flow characterization for mechanical recycling processes: a systematic literature review. Waste Manage.(New York. N.Y.) 149, 259–290. https://doi.org/10.1016/j.wasman, 2022.05.015.

Kroell, N., Maghmoumi, A., Dietl, T., Chen, X., Küppers, B., Scherling, T., Feil, A., Greiff, K., 2024. Towards digital twins of waste sorting plants: developing data-driven process models of industrial-scale sensor-based sorting units by combining machine learning with near-infrared-based process monitoring. Resour., Conserv. Recycl. (200), 107257 https://doi.org/10.1016/j.resconrec.2023.107257.

Kuchta, K., Guo, J., Woidasky, J., Auer, M., Schmidt, J., Pomberger, R., Tischberger-Aldrian, A., Kuhn, N., Anditsch, A, 2023. Vorstudie. Vergleich innovativer Identifikationsverfahren für Post-Consumer Leichtverpackungen. Endbericht.

Länderarbeitsgemeinschaft Abfall (LAGA) PN 98, 2001. Richtlinie für das Vorgehen bei physikalischen. chemischen und biologischen Untersuchungen im Zusammenhang mit der Verwertung/Beseitigung von Abfällen.

Lifocolor Farben GmbH & Co, 2021 KG. NIR-detektierbare-Masterbatches: lifocolor black & white. Lifocyle. https://www.lifocolor.de/site/assets/files/1608/21007_produktinformation_nir-schwarz_de_en_4-seiter-a4_screen.pdf.

Picuno, C., Alassali, A., Chong, Z., Kuchta, K., 2021. Flows of post-consumer plastic packaging in Germany: an MFA-aided case study. Resour., Conserv. Recycl. 169, 105515 https://doi.org/10.1016/j.resconrec.2021.105515.

Pitschke, T., Kreibe, S., 2020. Recyclingfähigkeit von Verpackungen: bewertungskatalog; INTERSEROH Dienstleistungs GmbH.

Plastic Europe, 2022. The circular economy for plastics: a European overview. https://plasticseurope.org/knowledge-hub/the-circular-economy-for-plastics-a-european-overview-2, [accessed 27.05.22].
Pomberger, R., 2020. Über Theoretische Und Reale Recyclingfähigkeit. Österreichische Wasser- und Abfallwirtschaft. https://doi.org/10.1007/s00506-020-00721-5.
Pretz, T., Raulf, K., Quicker, P., 2020. Waste. 4. Recycling. Ullmann's Encyclopedia of Industrial Chemistry. https://doi.org/10.1002/14356007.o28_o05.pub2.
RecyClass, 2020. Recyclable HDPE packaging with RecyClass. Recyclability evaluation protocol for HDPE containers released. https://recyclass.eu/news/recyclable-hdpe-packaging-with-recyclass, [accessed 11.08.23].
REMONDIS GmbH & Co. KG, 2023. Anlagenbeispiele aus den sechs REMONDIS Regionen. Region Rheinland – LVP-Recycling Erftstadt. https://www.remondis-entsorgung.de/anlagenverbund, [accessed 05.10.23].
Schmidt, J., Auer, M., Moesslein, J., Wendler, P., Wiethoff, S., Lang-Koetz, C., Woidasky, J., 2021. Challenges and solutions for plastic packaging in a circular economy. Chem. Ing. Tech. 93, 1751–1762. https://doi.org/10.1002/cite.202100110.
Statistisches Bundesamt (Destatis), 2023. Aufkommen an Haushaltsabfällen: deutschland. Jahre. Abfallarten. https://www.genesis.destatis.de/genesis/online?sequenz, tabelleErgebnis&selectionname=32121-0001&zeitscheiben=2 [accessed 23.09.23].
Stiftung Zentrale Stelle Verpackungsregister, 2023. Mindeststandard für die Bemessung der Recyclingfähigkeit von systembeteiligungspflichtigen Verpackungen gemäß § 21 Abs. 3 VerpackG. https://www.verpackungsregister.org/fileadmin/files/Mindeststandard/Mindeststandard_VerpackG_Ausgabe_2023.pdf.
Verpack, G., 2021. Gesetz über das Inverkehrbringen, die Rücknahme und die hochwertige Verwertung von Verpackungen (Verpackungsgesetz-VerpackG) i.d.F.v., 22.09.2021.
Wagner, J., Günther, M., Rhein, H., Meyer, P., 2018. Analyse der Effizienz und Vorschläge zur Optimierung von Sammelsystemen (Hol- und Bringsysteme) der haushaltsnahen Erfassung von Leichtverpackungen und stoffgleichen Nichtverpackungen auf der Grundlage vorhandener Daten. Umweltbundesamt. Dessau-Roßlau. INTECUS GmbH Abfallwirtschaft und umweltintegratives Management; Umweltkanzlei Dr. Rhein – Beratungs- und Prüfgesellschaft mbH.