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Research Paper

Strategies to enhance the circularity of non-bottle PET packaging waste based on a detailed material characterisation

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ABSTRACT

The compositions of Dutch lightweight packaging waste (LWP) and sorted products named "PET (Polyethylene terephthalate) trays" have been determined on object level. Additionally, the PET trays from both waste types were sorted in 16 categories representing their packaging use and material build-up. The material composition of at least 10 representative trays from each category was determined with chemical and thermal analysis, based on which the average material composition per category was established. Based on this data the average material composition of sorted PET tray products was approximated. The recyclability of the various categories of PET trays was assessed based on their material build-up. The most ubiquitous PET trays in Dutch LWP and sorted products were only found to be suitable to produce opaque recycled PET with mechanical recycling processes. Whereas only some more uncommon PET trays can be used to produce transparent recycled PET with mechanical recycling processes. Depolymerisation is deemed to be a more appropriate recycling process that will allow the production of transparent food-grade recycled PET.

1. Introduction

The European Union (EU) strives towards a circular economy for plastic packaging to curb the negative environmental impacts, reduce the use of primary resources and limit packaging wastes that need to be processed (European commission, 2018). Within Europe roughly 68 % of the polyethylene terephthalate (PET) packages are bottles, 21 % are trays, 8 % films and 3 % is miscellaneous (ICIS, 2024). Roughly 75 % of the European PET bottles are collected and sorted for recycling (ICIS, 2024). However, for PET trays this number is only 25 %. This reflects the state of development of the PET bottle collection & recycling infrastructure in comparison to the one for PET trays. Nevertheless, the recycling of PET trays holds promise, since the main material of the trays (PET) can in principle also be recycled to food-grade recycled PET (rPET).

The use of PET trays as food packages varies strongly between countries, which reflects differences in consumption behaviour. Many studies in Europe report the presence of PET trays in plastic packaging waste streams (Eriksen and Astrup, 2019; Gadaleta et al., 2023; Picuno et al., 2021). In Italy, PET trays account only for 2–3 % of the plastic packaging waste from separate collection (Gadaleta et al., 2023). Whereas, in the Netherlands, the amount of PET trays in plastic packaging waste streams is much higher. In 2019, the amount of PET trays sorted for recycling was 26 kton to 148 kton placed on the European market (Souder et al., 2024). The first reported share of PET trays in Dutch LWP (PMD in Belgium and the Netherlands, portfolio of plastic packages metal packages and beverage cartons) was 12.2 % in relation to the other plastic packages and stems from 2012 (Thoden van Velzen

Abbreviations: ATR-FT-IR, Attenuated total reflection Fourier transform infrared; CPET, Crystallised polyethylene terephthalate; DfR, Design for recycling; DKR, Deutsche Kreislauf und Recycling Gesellschaft; DSC, Differential scanning calorimetry; EFSA, European Food Safety Authority; EPR, Extended producer responsibility; EVOH, Poly(ethylene-co-vinyl alcohol); FMCG, Fast moving consumer good; HDPE, High density polyethylene; IR, Infrared; LDPE, Low density polyethylene; LWP, Lightweight packaging waste; MFA, Material Flow Analysis; MTOAB, Methyl-trioctyl ammonium bromide; PE, Polyethylene; PET, Polyethylene terephthalate; POM, Polarised optical microscopy; PP, Polypropylene; PRE, Plastics Recyclers Europe; PMD, Portfolio of LWP in Belgium and The Netherlands (Plastic, Metals and Drink cartons packaging); PS, Polystyrene; PSA, Pressure sensitive adhesive; PVC, Polyvinyl chloride; SP, Sorted product.

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et al., 2014), and it slowly grew to 14 % in 2014 and to 15 % in 2017 (Brouwer et al., 2019, 2018). This implies that PET trays are the largest plastic packaging category in Dutch LWP waste. Consequently, the recycling of PET trays is vital for the Dutch extended producer responsibility (EPR) organisation to attain the legal recycling target of 47 % in 2024, 50 % in 2025 and 55 % in 2030 (Staatssecretaris, 2014).

It is unclear when the first PET trays appeared on the Dutch market. A tray producer reports that in 1993 they switched from using polyvinyl chloride trays to PET trays for minimal processed vegetables. Furthermore, around 2000 most Dutch meat packers started using modified atmosphere packages with PET-based top-sealed trays (Thoden van Velzen and Linnemann, 2008).

Prior to 2017, the PET trays were added to the sorted product named Mixed Plastics (DKR 350 (Gruene Punkt, 2023)). However, the recyclers of Mixed plastics are only interested in producing a mixed polyolefin product and regard the presence of PET trays as undesired. Therefore, from 2017 on the PET trays were sorted into a separate sorting product called “PET trays” and were stored for future recycling. The development of recycling technologies for PET trays did, however, not develop as fast as hoped. Only in 2020, the first substantial amounts of sorted PET trays were recycled at a newly erected facility of Cirrec in Duiven, the Netherlands (Cirrec, 2023; Faerch group, 2023; Lybaek, 2024). From 2022 on, almost all sorted Dutch PET trays are processed there into a light-green, opaque food-grade PET, that is used to produce CPET (crystallised polyethylene terephthalate) meal trays. The recycling process this company developed is proprietary and in essence a complex mechanical recycling process.

In response to recycled content policies (European Parliament and Council, 2019; Staatssecretaris, 2022) and Plastic Pact Pledges (Ellen MacArthur Foundation, 2023; Kahlert et al., 2022), many retailers and food companies are procuring rPET that is transparent and food-grade to produce trays to pack their fresh food products in (Eunomia, 2022; ICIS, 2024). Up to 2022, most rPET used in trays originated from beverage bottles. However, with the increasing recycled content targets for beverage bottles, less rPET is available on the market for trays. This bolsters the need to develop new recycling processes which can convert sorted PET trays into transparent food grade rPET.

Within the public literature the recycling of PET trays has hardly been described. The studies on multilayer packaging are often carried out on the laboratory-made blends and focus on studying their recyclability (Seier et al., 2022; Trossaert et al., 2022; Uehara et al., 2015; Ügdüler et al., 2021), or to improve the mechanical properties of the blends, but these blends are still opaque (Delva et al., 2019). Other studies have dealt with characterising packaging by some thermal techniques (polarized optical microscopy (POM), attenuated total reflection-Fourier transform infrared spectroscopy (ATR-FTIR), elemental composition analysis, etc.) (Roosen, 2020; Seier et al., 2022; Thoden van Velzen et al., 2020). One of them, Thoden van Velzen reports the mechanical recycling of three different clean PET trays to opaque rPET. The sealing medium (either LDPE, hotmelt or an alternative adhesive) on the trays is finely dispersed within the PET matrix to form a hazy blend. Furthermore, the recycling process lowered the average molecular weight of the PET chains, as was apparent from the drop in intrinsic viscosity from 0.65 to 0.47–0.57 g/dl after recycling (Thoden van Velzen et al., 2020). The intrinsic viscosity of PET is a measure of its molecular weight reflecting the tensile strength of a material and determines its applicability. To compensate the loss of IV, rPET is subjected to Solid State Polycondensation (SSP) to its molecular weight (Fitaroni et al., 2020; Welle, 2014). A recent study also studied the impact to PE-EVOH-PE top-films on the quality of the rPET and found that the presence of EVOH reduced the size of the PE blend particles in the PET matrix. Furthermore, it demonstrated that the large difference in processing temperature between PET and PE causes the PE to branch and crosslink during recycling, further lowering the quality of the recycled material (Seier et al., 2022). Compatibilisation of PET-PE blends has been reported in several studies (Delva et al., 2019) which results in opaque materials. Also, chemical recycling solutions have been proposed by various studies (Jansen et al., 2015; Schyns and Shaver, 2021; Zhou et al., 2020). These approaches hold promise to produce more pure, transparent rPET, but are likely to consume more chemicals and energy than mechanical recycling (Schyns and Shaver, 2021).

This article aims to thoroughly describe the material composition of Dutch PET trays to assess the suitability of recycling strategies. Therefore, PET trays are characterised that are present in Dutch LWP and in the contrived sorted product (DKR 328–5 (Gruene Punkt, 2023)). The characterisation is executed on two levels (objects and materials). The LWP and sorted products are studied on the level of objects at which 12 main different categories of PET trays (e.g., transparent multilayer meat, cheese or fish trays, clamshells and top-sealed trays, containers for eggs, pots for yogurt…) are present on the Dutch market. Furthermore, the material composition of all these categories of PET trays is elucidated with a combination of analysis techniques (e.g., ATR-FTIR spectroscopy, DSC, saponification, etc.) which do not only render information on the share of PET in the 12 main types of PET trays, but also in the various different polymers and materials present in these types of PET trays. Combining the sorting data on the object level with the average material composition per packaging category results in a description of recycling feedstock on the level of materials. Therefore, by defining the material composition of PET tray waste, which has received little attention in the scientific literature, but has shown a high contribution in the mass flows of post-consumer plastic packaging (ICIS, 2024; Souder et al., 2024), this study can be used to estimate the recycling rate for PPW providing data for the mass flow models (Antonopoulos et al., 2021; Ghosh et al., 2023; Gracida-Alvarez et al., 2023; Kroell et al., 2023; Picuno et al., 2021). Also, since multilayer is a plastic stream that has not yet been well-characterised, this study for PET trays, complementary and consistently with previous studies (Seier et al., 2023; Roosen et al., 2020a; Ügdüler et al., 2020), helps to establish a clear understanding for non-bottle PET packaging waste. Though, despite the local nature of the study, it can also be considered a significative contribution for the PPW recovery framework beyond the Dutch borders. Hence, this dedicated material definition for PET trays, correlated with the resulted design for recycling guidelines, could be used to complement material flow analysis (MFA) (Brouwer et al., 2018) studies by helping industry technical options and sorting policies, pushing to redesign the plastic recycling network toward a more circular economy.

2. Materials and methods

2.1. Approach

Three main tasks were executed: (i) the analysis on object level of LWP samples taken at the input of the plastic waste sorting plant and of samples of the PET-tray sorted product (SP) taken at the output of the plastic sorting waste (Figure 1a); (ii) material characterisation by chemical and thermal analysis of the PET-tray categories on material level; (iii) assessment of the suitability of PET trays for various recycling approaches.

2.2. Plastic waste samples

Samples of PET trays from two different stages of the PET tray value chain were studied: LWP from the collection agency of Rova, Zwolle (the Netherlands); PET-tray-sorted products (SP) from the sorting facility of Attero, Wijster (the Netherlands) (Figure 1a,b). LWP is collected differently according to municipality policies, and this is delivered to sorting facilities (such as Attero) via cross-docking stations.

Two types of LWP samples (1, 2) have been supplied from the collection agency, one derived from kerbside collection with bags from households in Zwolle city and one from the kerbside collection through bins from rural Olst-Wijhe municipality; furthermore, two samples of rigid PET-tray SP (3, 4) were picked up from the sorting plant. Further

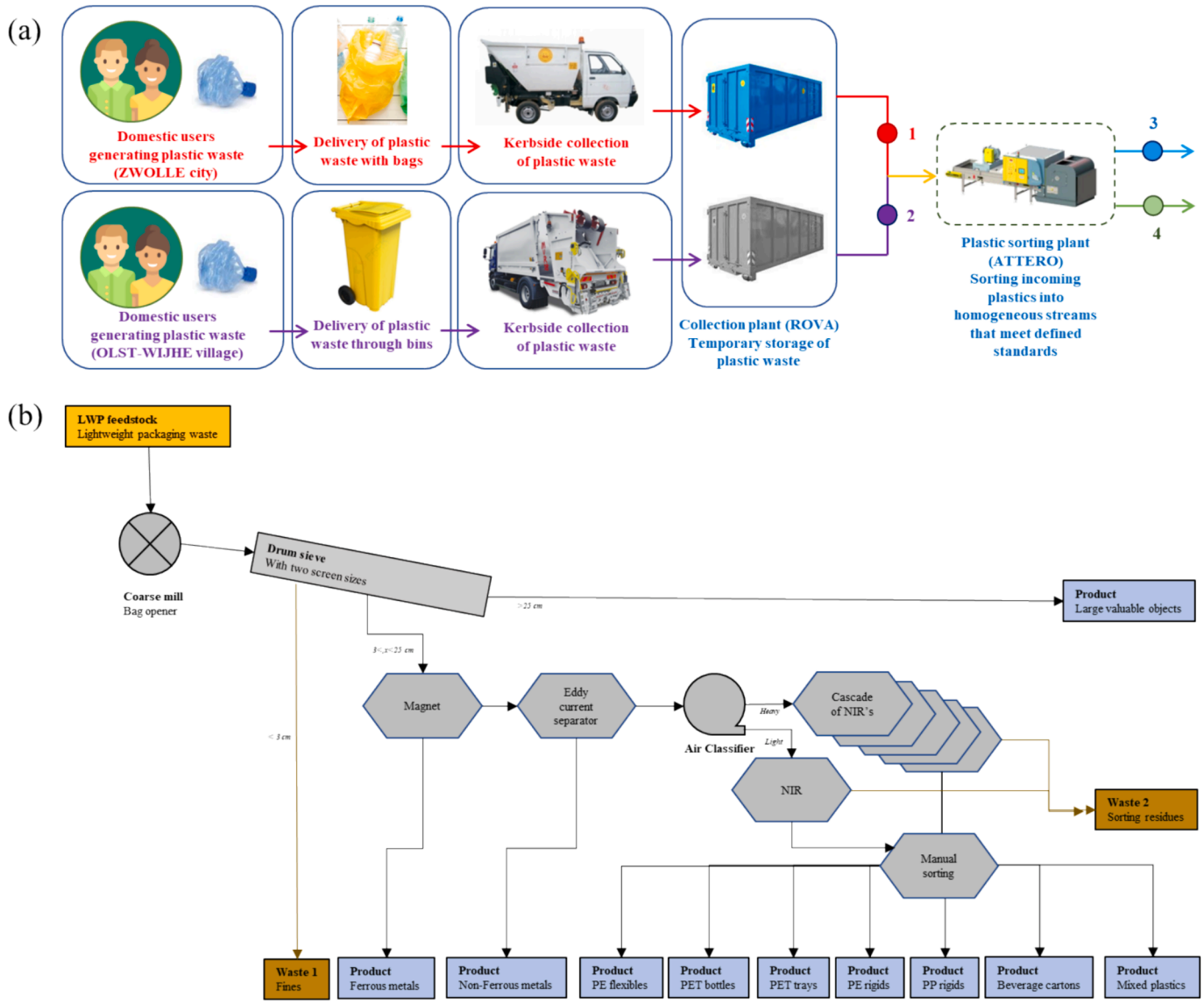

Fig. 1. (a) Origin of study samples and (b) process diagram of the Attero sorting plant (The Netherlands).

information on the characteristics of the samples investigated can be found in Table S1.

2.3. Sorting of PET trays in LWP and SP samples

The plastic waste samples were sorted according to an existing sorting protocol (Thoden van Velzen et al., 2018).

The samples of packaging waste, arrived in big bags with a polyethylene internal bag or as pressed bale, were stored at 7 °C to suppress biological activity and moisture loss.

First, the samples of LWP were sorted manually into the main material categories (plastic, beverage cartons, paper & board, textile, ferrous and non-ferrous metals, glass, organic fraction) by defining the percentage by weight for each fraction (Table S2).

Then, the plastic waste fraction was further sorted into (i) main-polymer type flows (polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and black plastic) through visual inspection, when the product had a polymer identification label, and confirmed using the near-infrared (NIR) scanner (X. Chen et al., 2021), and into (ii) packaging types (bottle, flask, other rigids (trays), flexibles, laminated flexibles, and non-packaging objects). A NIR scanner named IOSYS SIRO has been used (Individual Optical System, IOSys Germany).

Subsequently, the PET trays were further categorised into 12 main categories (Figure 2), based on the composition and previous use (e.g., type of packed food), and eventually, other subcategories were chosen to reflect the differences in material composition in the same category.

Each category is related to the previous use as packaging, which was shown on the package label, classification in product categories was done manually based on visual inspection of the product in general and based on the label description.

Next, also the two samples of PET tray SP were sorted in the same manner: first by material, then for the plastic stream by polymer type and its packaging subcategories, and finally by PET tray categories.

2.4. Material characterisation of PET tray categories

Representative samples of PET-tray categories were subjected to chemical and thermal analyses, to determine their material composition. From each of all the categories (12 main categories and 4 subcategories (the analysis excluded non-transparent packaging categories as they were unsuited to the objective of the study, which was to produce transparent rPET)) 10 representative packages were analysed. PET trays were predominantly taken from the sample 1 of LWP, as these were the

Fig. 2. PET-tray categories considered in the study: 1 = Transparent meat, cheese, fish, pasta, vegetarian trays (multilayer); 1a = Transparent meat, cheese, fish, pasta, vegetarian trays (mono PET); 1b = Coloured meat trays; 2 = Bowls and fresh salad trays; 3 = Clamshells and top-sealed trays for fresh fruits, vegetables, nuts trays; 3a = Clamshells and top-sealed trays for fruit with PE bubble wrap inlay with hotmelt; 3b = Clamshells and top-sealed trays with moisture absorber inlay with hotmelt; 4 = Smearable salads trays; 5 = Clear trays and clamshells for cookies and bakery products (mono PET); 5b = Opaque trays for cookies and bakery products; 5c = Clear trays for pancake (multilayer); 6 = Non-Food blisters; 7 = Thermoformed trays for cured meat products and sliced cheese; 8 = Container for eggs; 9 = Flat trays to support sliced meat and cheese products; 10 = Jars (e.g., peanut butter, creams); 11 = Loose lids and caps; 11a = Coloured loose lids and caps; 12 = Pots for yogurt.

least contaminated with surface grime and dirt. This LWP sample was less contaminated, less deformed and younger (organic decomposition of contained food residues had progressed less far), because it was collected in transparent bags instead of wheelie bins (sample 2). The sorted product samples (3 and 4) were in all these aspects worse, see Table S4.

Samples of PET trays were disassembled into its components. The separable packaging subcomponents that can be physically separated from the tray, the main packaging part, were manually split off and individually weighted. These components are *top films*, that could be transparent or printed, mono- or multilayer, *labels* that could be made of paper or plastic, and that could be placed on top, on the bottom, or to the side of the tray, and eventually, also *absorbers*, that could be made of cellulose or plastic. Each component of the packaging may be composed of different polymers and materials; all components of the object were analysed to determine its material identity, which is further explained in the section below. At the end of the repeated disassembly procedure for the 10 samples per category, the average material composition per category was calculated.

2.4.1. ATR-FTIR analysis

The type of of PET tray components was determined with a Bruker Alpha Fourier Transform Infrared spectroscopy (FTIR) instrument equipped with a platinum ATR single reflection diamond sampling module (Bruker Optics). Data points were collected between the wavenumber range of 400–4,000 cm^{-1} at a resolution of 4 cm^{-1} (Baskaran and Sathiavelu, 2020), controlled by Optics User Software (OPUS) version 8.1. Spectra analyses were determined using OPUS version 8.1. Infrared spectroscopy measures the frequencies of infrared light absorbed by the bonds that constitute a compound. Each type of bond has a natural frequency or vibration energy. The region of the IR spectrum between 600–1,400 cm^{-1} is known as the 'fingerprint', so, IR spectroscopy can easily confirm the identity of an unknown compound by spectral comparison with a known compound (He and Gilpatrick, 1999). In particular, through IR analysis the polymers constituent each packaging item were identified. ATR-IR technology only analyses the first micron thickness of a material, to supplement this limitation, characterisation involved the use of complementary technologies such as DSC and saponification that analyse the full material.

2.4.2. Saponification

Roughly 5 g of PET samples were dissolved in a solution NaOH 4 M, 20 g NaOH (NaOH; M = 40.0 g mol^{-1}, ρ = 2.13 g cm^{-3}, Sigma-Aldrich), 200 ml of demineralised water, 250 mg MTOAB (Methyl-trioctyl ammonium bromide). To carry out the saponification (Spaseska and Civkaroska, 2010), 250 ml glass Scott bottles with magnetic stirring bars have been placed with their bottoms in a water bath at 95 °C and stirred magnetically at 300 rpm overnight for 16 h. Later, the solutions were filtered and the residues were dried in aluminium trays in the oven at 105 °C for 2 h. By weighing this residue and comparing it with the starting total sample's weight, it was possible to approximate the share of PET in the packaging component under the assumption that the residual material is not saponifiable, which means that in the presence of a strong base it does not hydrolyse, unlike PET. Which under the same conditions breaks down into the corresponding alcohol and acid, this is true for most other materials and polymers of PET tray packages. In particular, these residues were then analysed by IR to identify the constituent polymers.

2.4.3. Differential scanning calorimetry (DSC)

DSC studies (Carte and Moet, 1993) were carried out on samples of 10–15 mg of PET-tray components of all categories, with a Perkin Elmer DSC-8000 in twofold. Each tray was grinded into flakes, roughly 15 mg of these flakes were weighted and closed into aluminium cups. A specific program was carried out with the Perkin Elmer DSC-8000 to determine the polymer contents: conditioning for 2 min at 0 °C, heating at 100 °C. $min^{-1}$to 130 °C, conditioning for 20 min at 130 °C, cooling at 100 °C. min^{-1} to 0 °C, conditioning for 3 min at 0 °C, heating at 10 °C.$min^{-1}$to

300 °C. The content of different polymers was derived from the second heating curve after cooling at 10 °C.min^{-1}, assuming the correspondent melt enthalpy that each polymer (PET, HDPE, LDPE, etc) would absorb in case of 100 % content of it. The common use of commercial DSC equipment is to measure physical properties such as transition temperatures, and heat of fusion, and to study polymerisation kinetics and crystallisation kinetics under isothermal conditions. Melting peaks and glass transition temperatures were associated with particular polymers by comparing measured values with references and using information obtained from IR analysis (He and Gilpatrick, 1999).

2.4.4. Data analysis

The average material composition of the PET tray sorted products was determined by disassembling the packages into their components and weighing all components separately. This was repeated for 10 individual packages of a category and the results were averaged. At the end of the repeated disassembly procedure for the 10 samples per category, the average material composition per category was calculated, considering the results of the analysis described below.

The average material composition of all other objects (non-PET-tray) was taken from Brouwer et al. (Brouwer et al., 2018) which is based on the composition of LWP samples from 2010 to 2017. The data were combined to obtain average material compositions of the sorted product samples (3 and 4) and standard deviations.

The speciation of PET trays into categories is based on the different uses (packaging of different products) which often relates to different material compositions of these trays. For some packaging components it was difficult to judge visually whether it was composed of one material or multiple materials (see Table S4). This occurred a few times for trays which could either be a mono-PET tray or a multi-layered PET tray. In these instances, ATR-FTIR spectra of both sides of the component were recorded. Based on the results of the analysis of the tray, it was assigned to the correct category or subcategory. Anyway, further characterisation was performed, especially if the ATR-FTIR analysis showed that both sides of the packaging item did not consist of the same polymer.

Subsequently, DSC analysis and saponification allowed quantifying the different polymers' content in trays or films. Through DSC it is possible to estimate the polymeric composition, as this method uses small samples that might not be representative for the whole package, it can only detect polymers that possess a thermal transition (which is luckily the case for the most relevant polymers in PET trays) and it is not very reliable when the share of polymers is below 2 %. For this quantification, the Eq. 1 was applied.

$$\%polymercontent = \frac{\Delta H_i^{Polymer}}{\Delta H_{100\%}^{Polymer}} * 100 \quad (1)$$

Hence the share of several main polymers in studied packaging components could be approximated. The identity of several main polymers was established from the recorded melting temperatures (e.g. it was possible to quantify the content of PE and PET: T_m^{HDPE}=130 °C; T_m^{LDPE}= 125 °C; T_m^{PET}=250 °C), through the value of enthalpy realised or absorbed, it is possible to quantify the content of that polymer, relating the enthalpy value in the DSC curve ($\Delta H_i^{Polymer}$) to the enthalpy realised corresponding to the 100 % content of the polymer in the sample ($\Delta H_{100\%}^{Polymer}$). The DSC analysis made it possible not only to identify polymers, but also to quantify the content of each polymer in each sample.

The saponification process allowed to determine the "non-saponifiable" content in the multi-material tray. From the commonly applied packaging materials only PET dissolves in this process and this enables the approximation of the share of residual material (read: non-PET material), after which this isolated residue can be identified with IR analysis. By averaging the non-saponifiable weight values of the samples of the same categories was determined the average weight ($W_g^{non-saponifiablecontent}$) of it and then the percentage, as in Eq. 2.

$$\%non-saponifiablecontent = \frac{W_g^{non-saponifiablecontent}}{W_{gtot}^{sample}} * 100 \quad (2)$$

At the end of these analyses, the amount of polymer content identified by DSC analysis and saponification was averaged to obtain an indicative value of the amount of polymer contained in each object component of each PET tray category (see Table 1).

After analysing all the components, it was possible to obtain the average weight of polymers, paper, and metal contained for each packaging item, and when added together, the total average value of the contents of the complete package waste per category (Eq, 3):

$$W_{polymer}^{PACKAGE} = W_{polymer}^{TRAY} + W_{polymer}^{TOPFILM} + W_{polymer}^{LABEL} + W_{polymer}^{ABSORBER} \quad (3)$$

Finally, for each category, the share of materials in a studied packaging was calculated by Eq. 4. Averaging the results for 10 individual packages resulted in average shares of material for each packaging category.

$$\%W_{polymer}^{PACKAGE} = \frac{W_{polymer}^{PACKAGE}}{W_{TOT}^{PACKAGE}} * 100 \quad (4)$$

2.5. Design-for-recycling guidelines definition

Design-for-recycling (DfR) guidelines are material-centred design approaches, that support the industry to improve the overall recyclability of plastic products. These guidelines, developed in Europe by associations, like Plastics Recyclers Europe (PRE), provide a comprehension of the compatibility of different elements of packaging (caps, labels, or adhesives) with certain recycling streams (Lange, 2021).

Table 1
Average material composition per PET-tray category (* PSA = Pressure sensitive adhesive).

Material composition, [% m/m]							
	PET [%]	PE [%]	PP [%]	Other plastic [%]	Paper [%]	Metal [%]	PSA [%]
1	73.0 ± 42.1	15.6 ± 8.4	1.3 ± 2.1	0.1 ± 0.6	8.3 ± 15.7	–	1.7 ± 2.8
1a	74.9 ± 25.7	11.4 ± 3.8	1.3 ± 1.8	0.0 ± 0.2	10.3 ± 17.3	–	2.1 ± 7.7
2	96.7 ± 20.5	1.8 ± 1.6	0.4 ± 0.6	0.8 ± 0.6	0.0 ± 0.1	–	0.4 ± 0.1
3	95.9 ± 31.8	1.6 ± 0.8	–	0.4 ± 0.5	1.5 ± 2.0	–	0.6 ± 2.1
3a	93.5 ± 7.2	3.5 ± 0.5	–	–	2.7 ± 1.8	–	0.3 ± 0.2
3b	88.5 ± 43.4	4.9 ± 1.8	–	0.8 ± 1.1	5.0 ± 2.8	–	0.8 ± 2.3
4	94.1 ± 27.9	1.9 ± 0.9	0.1 ± 0.4	1.1 ± 1.3	1.7 ± 0.9	–	1.0 ± 1.0
5	97.4 ± 51.6	0.3 ± 0.8	–	0.3 ± 0.8	1.4 ± 1.6	–	0.6 ± 1.6
5c	81.9 ± 38.6	15.4 ± 8.1	–	–	2.0 ± 1.6	–	0.7 ± 1.5
6	88.6 ± 111.8	1.1 ± 2.1	0.8 ± 2.0	–	7.1 ± 16.8	–	2.4 ± 16.7
7	80.7 ± 27.5	13.5 ± 12.1	–	0.1 ± 0.3	4.2 ± 2.3	–	1.4 ± 2.2
8	97.5 ± 48.2	1.0 ± 0.9	–	–	1.1 ± 1.1	–	0.4 ± 1.1
9	99.1 ± 44.9	0.9 ± 1.2	–	–	–	–	–
10	70.4 ± 59.4	–	27.3 ± 22.6	–	1.1 ± 1.7	–	1.1 ± 1.7
11	96.8 ± 90.7	0.6 ± 0.7	–	0.3 ± 1.0	1.7 ± 3.3	–	0.6 ± 3.3
12	71.4 ± 23.3	1.7 ± 1.2	–	0.1 ± 0.2	23.6 ± 19.7	0.6 ± 1.3	2.6 ± 18.6

The 16 analysed categories of PET trays have been classified on three different degrees of mechanical and chemical recycling compatibility based on their material composition. On the basis of the composition of PET trays, identified in the characterisation phase of this study, new classification criteria and guidelines were outlined, which complement the existing ones, considering the current state of recycling technology.

To assess of the feasibility of mechanical recycling, this classification was executed with the ultimate goal in mind of closed-loop mechanical recycling, in other words the production of new transparent, food-grade recycled PET from the PET tray waste.

The design-for-chemical-recycling criteria are less well-developed than those for mechanical recycling, as "chemical recycling" is an umbrella term for multiple technologies (Vollmer et al., 2020) and there is much less industrial experience with chemical recycling of plastic waste than with mechanical recycling (Solis and Silveira, 2020)(Quicker et al., 2022). This paper will refer to the chemical recycling technology of depolymerisation, as this is the most common and suited for PET waste. Several depolymerisation processes (glycolysis, methanolysis, and hydrolysis) have been described that fragment PET into monomers (e.g. terephthalic acid, TPA; ethylene glycol EG) In these processes, the PET waste is reacted with either water, an alcohol or an amine to form soluble or volatile monomers, which are purified and then repolymerised (Abedsoltan, 2023).

2.5.1. Assessment criteria for mechanical recycling

Based on the results obtained from the characterisation of PET trays in this study, new self-invented criteria classification and guidelines were outlined, supplementing existing ones (PETCORE Europe, 2020; Recyclass, 2021). The PET tray categories were classified into three levels of mechanical recyclability (high, medium and low) based on their average material composition (Watkins et al., 2020).

The recyclability assessment criteria taken into account include: (i) the minimum PET content that is recoverable and valuable for the primary packaging component (i.e., tray), since all packages in the system should be made of a restricted amount of plastics (two or three polymer types)(Brouwer et al., 2020); (ii) the use of non-food-contact packaging has been considered to be a penalising aspect in reaching closed-loop recycling (Franz and Welle, 2002; Welle, 2008; as it can potentially introduce hazardous chemicals. Franz et al., 2004; Geueke et al., 2018); (iii) the impact of polymer contamination on the package's sortability; such as external packaging presence, and other factors that may affect sortability through the current European recycling technologies; since the packages should be easily recognised by automatic sorting machines and should be easily separate in an efficient manner in the recycling process (Brouwer et al., 2020; Feil et al., 2019); (iv) the maximum content of other polymers (i.e. PE as the polymer present in the analysed trays). The average value indicated by Roosen et al. (Roosen, 2020), 6.6 % of PE content in the tray, for inseparable polymeric contamination per layer of PET trays was taken as the limit value to identify the minimum level of recycling compatibility; (v) the presence of elements that may affect the transparency of the final recycled PET, such as colour, and ink, that could also contain metals and halogens and raise issues towards regulatory compliance due to the possible migration of such contaminants from the recycled material (Roosen et al., 2020); (vi) the presence of closure systems (which type of adhesive has been used), such as the material used and the type of application (Silva et al., 2023); (vii) the presence of other components, such as labels and pads, and type and method of application (Roosen et al., 2020).

To assign a quantitative level of recyclability to each category, a method was developed based on the abovementioned criteria. A PET tray is considered to be fully compatible with a recycling technology in case it can be processed and yields best quality of recycled PET. The medium compatibility corresponds to the second choice for each tested packaging specification that could slightly impact its recyclability (for example engendering the recycled plastic opaque instead of transparent, or non-food-grade, etc.). The low compatibility indicates that the product presents criticalities for mechanical recycling that are difficult to overcome by the current process technologies, characteristics that should be avoided because these could strongly impact the quality of the recycled PET.

With the aim of obtaining a final classification of compatibility of all categories of PET trays to recyclability, the following scores were awarded: in case of the complete correspondence of the category to the criterion under consideration given recyclability: 1; in case of no correspondence to recyclability: 0; and to indicate the intermediate level of compatibility between the tray property and the related criterion: 0,5 (see Table S8).

2.5.2. Assessment criteria for chemical recycling

The PET-tray categories were ordered into three levels of chemical recyclability, considering their composition and compatibility with the depolymerisation.

Three DfR criteria based on common sense have been postulated: (i) accessibility of PET; the object should have the PET on the outside and not as an internal layer between inert layers (Ügdüler et al., 2021; Vogt et al., 2021); (ii) absence of other depolymerisable polymers; in case other polymers are present that contain bonds that can also be broken under the conditions of the depolymerisation process, there is substantial chance the process is negatively influenced. Either additional reactants are used that do not render more products or an impure product is obtained; (iii) absence of impurities (e.g. additives, inks) that can negatively affect the purity of the resultant monomers (Ügdüler et al., 2020; Agostini et al., 2022). Such impurities and their depolymerisation products formed during the recycling process can be present in the product as impurities or they can complicate the purification process itself (gel-forming during filtration) (Karayannidis and Achilias, 2007; Volmajer Valh et al., 2022).

The degree of compatibility to this recycling technology was established using the same procedure applied for the assessment of mechanical recyclability, following the same scoring method, to obtain a final classification on chemical recycling compatibility.

3. Results and discussion

3.1. PET trays in LWP and SP samples

The composition of the four samples in the main categories is listed in Table S3. The more elaborate composition in relation to all object categories is available in the supplementary material. Furthermore, the average composition of the LWP samples is depicted in Figure 3 a) and of the sorted products samples in Figure 3b).

The LWP samples 1 and 2 are indeed mostly constituted of the targeted materials: plastic packaging waste, beverage cartons and metal packages. Additionally, non-targeted contributions were present (organic waste, paper & board, glass, textile). The main difference between the two samples of LWP is the larger share of organic waste in sample 2 (with 14.1 % compared to 1.1 % in the sample 1). The share of PET-trays constitutes roughly 10 % of both LWP samples and roughly 15 % of the plastic packages present in the LWP. Hence, the PET trays form the largest plastic packaging fraction (as highlighted in Figure 3 in light blue). The analysed LWP waste samples correspond to the incoming waste stream for the sorting plant (as shown in Figure 1b). On the other side of the sorting facility, the sorted products leave the plant. The EPR organisation decides on type of sorted products that have to be made and this comprises for the Netherlands: PET bottles, PET trays, PE, PP, flexible packages, mixed plastic, ferrous metals, non-ferrous metals and beverage cartons.

The PET trays sorted products (samples 3 and 4) contains only a small amount of non-PET objects, such as PP and PE based packages due to sorting errors. Indeed, the sorted products are mainly made up of PET tray products, with a percentage from 70 % to 90 %, as is clear from Figure 3b), which implies that one of the studied PET tray sorted

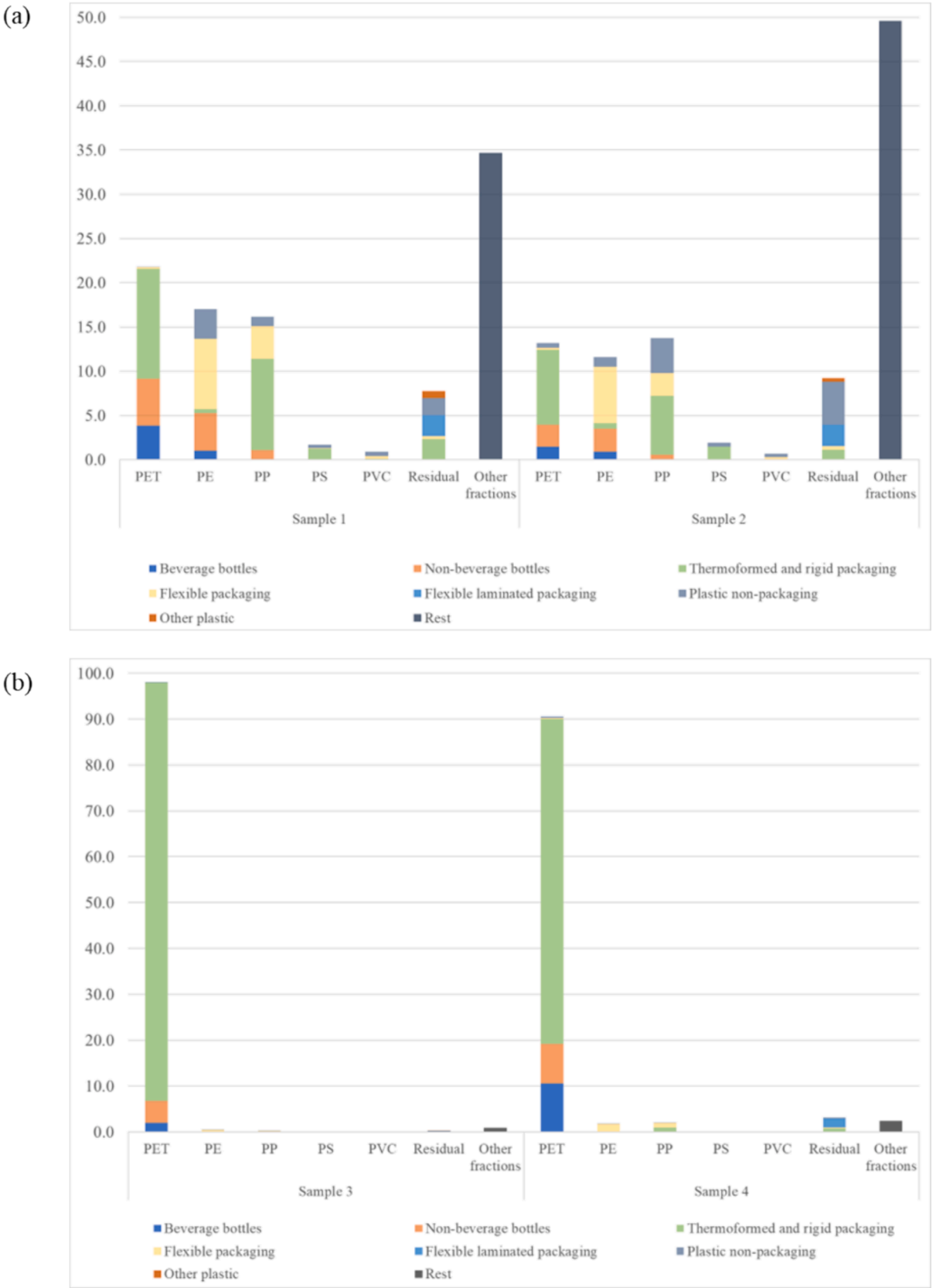

Fig. 3. A) average composition of the two lwp samples: Sample 1 = first LWP sample; Sample 2 = second LWP sample (both from the collection agency); b) Average composition of the two SP samples: Sample 3 = first PET tray sorted products sample; Sample 4 = second PET tray sorted products sample (both from the sorting plant).

products was just short of reaching the 75 % of PET limit given in the DKR 328–5 specification. The most common type of non-targeted objects in these sorted products are PET bottles; mainly non-beverage bottles and small clear beverage bottles (with a volume of 0.5 L or less); large PET bottles are collected via a deposit refund system and are less common in LWP. Both the EPR organisation and the PET tray recycler aim to keep the share of PET bottles as low as possible for different reasons. The EPR organisation aims to optimise its revenues from selling sorted products and under favourable market conditions PET bottles command a higher price than PET trays (exceptionally this is not the case in 2023). The PET tray recycler aims to produce food-grade recycled PET, which can be jeopardised by shares of non-food PET bottles exceeding 5 %, as EFSA demands the feedstock should be composed of 95 % food packages in its positive opinion (Barthélémy et al., 2014; Franz and Welle, 2020).

The appearance of PET trays in the sorted product is markedly different as compared to the same objects in the LWP. Most PET trays in the LWP are easily recognisable, still have their original shape and the level of soiling with surface grime is limited. Whereas the same trays that are retrieved from the sorted product are crushed to semi-two-dimensional objects and heavily soiled. Furthermore, most trays in the LWP still possess readable labels and the labels on trays from the sorted products are often missing or scuffed making them unreadable. This crushed and flattened nature of the presence of PET trays complicates the sorting process in the sorting plant. Often such deformed trays clamp in impurities such as organic waste (food residues) and flexible packages.

The innovative aspect of this study lies in the classification of PET tray products into categories, which allows us to approximate the material composition of the PET tray sorted products and therewith propose suitable recycling strategies for this feedstock. The result of this classification in 16 categories for the four samples is shown in Figure 4.

Most PET trays in the Netherlands are used to pack meat, cheese, fish and vegetarian meat replacers (category 1) and cured meat and sliced cheese products (category 7) and fruit and vegetable products (categories 2,3). In general, the PET trays in the sorted products were more challenging to recognise and categorise than those in the LWP, see Table S4. This was especially true for category 1. The presence or absence of an internal PE layer can easily be established for clean PET trays from the LWP by looking at the surface gloss and feeling the surface friction. This is, however, no longer possible for highly soiled and deformed PET trays from the sorted product. In these cases, infrared spectra were recorded of both sides of the tray, as described in section 2.4.

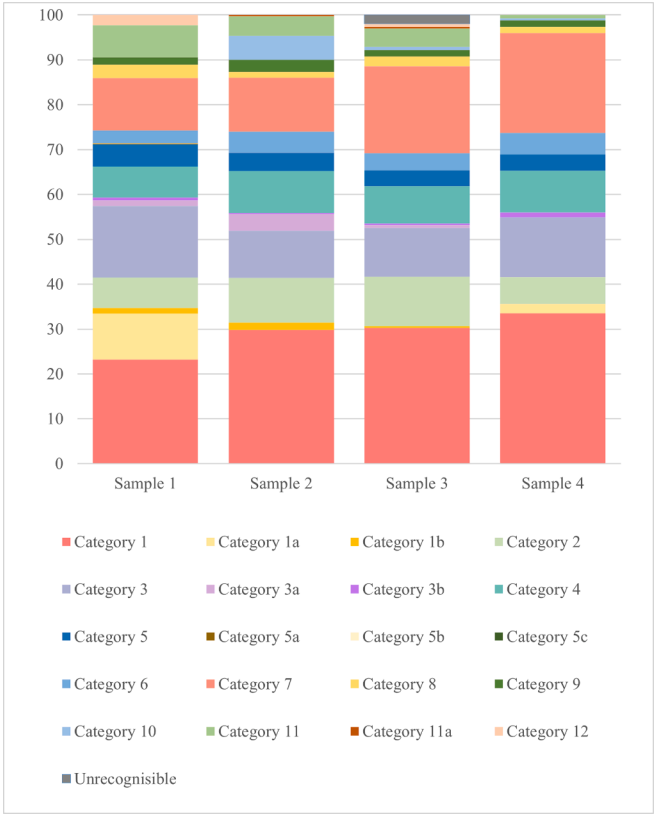

Fig. 4. Composition of LWP and SP samples in terms of the 16 categories of PET tray present.

It is clear from Table S3 that the main difference between the PET-trays in the LWP and in the SP samples is related to the difficulty in recognising the different types of PET trays in the SP samples. In the SP samples, there is a fraction of uncategorisable trays because they are excessively altered, missing in the LWP samples. Furthermore, trays appear flattened and pressed in different shapes, trays that have lost labels, top film, and any kind of indication as to previous use. And especially, high levels of dirt, and contamination by mould and spoiled organic material.

A second difference is the lower shares of coloured and opaque trays in the SP samples as compared to the LWP samples, which relates to the sorting policy of the sorting facility to only sort transparent PET trays in the SP.

3.2. *Material composition of PET tray categories*

The average composition of each category of PET trays in terms of components is listed in Table S5. It should be noted that this composition was based on the composition of the waste sorted by LWP, which may not correspond to the composition of the entire packaging as it is sold in shops, as citizens often remove components as top-films and labels before discarding the tray in the LWP bin/bag (indeed we found that many samples had lost some components, as closure films or labels) (Thoden van Velzen et al., 2020, 2019). Simultaneously, this material composition also does not reflect the composition of the trays in the sorted product, as some of the trays in the sorted product also are devoid of components such as top-films and labels, due to the mechanical action during sorting.

As is evident from Table 1, the PET content varies from category to category from a minimum of 70 % (category 10) to a maximum of 99 % (category 5). This depends on the number of components the package is made of. Indeed, the categories with a low PET content usually contain non-PET components: category 10 is made up not only of the main body (mono-material) which alone contributes to the PET content, but also of a PP cap with 27.3 % of the weight (see Table S5). Furthermore, the categories with a lower PET content (such as 1, 7, 12) include those whose main body is multi-material. Conversely, the categories with a high PET content correspond to the mono-material categories (2, 3, 3a, 4, 5, 8, 11) or the categories whose components were not present in the LWP sample, such as category 9 consisting of 100 % main body and thus 99.1 % PET in the entire composition.

Besides the share of paper, which is usually associated with labels and absorbers, the polymers with the highest weight shares are polypropylene and polyethylene. PP is mostly contained in the labels and films, whereas PE is often part of the multi-layered PET-PE tray, indeed trays belonging to multilayer categories are generally made of PET and PE.

With the average material composition per PET tray category (Table 1) and the object composition of the sorted products (data reported in Table S5, graphically showed in Figure 3b) the average material composition of the sorted products was approximated, see Table 2. In this table the PSA content has been incorporated in “Other plastics” percentage.

Table 2
Average material composition of the sorted products.

PET [%]	PE [%]	PP [%]	PS [%]	PVC [%]	Other plastics [%]	Paper [%]	Metal [%]	Glass [%]	Undefinable [%]
79.2 ± 15.2	8.6 ± 3.1	2.6 ± 0.8	1.1 ± 1.5	1.1 ± 0.0	1.8 ± 1.1	4.4 ± 0.3	0.3 ± 0.2	0.6 ± 0.0	0.2 ± 0.3

3.3. Suitability for recycling processes

The suitability of the PET trays to produce food-grade transparent recycled PET with mechanical recycling processes and depolymerisation processes is explored. For the mechanical recycling processes this is executed by comparing the material composition of the PET tray categories with DfR guidelines and scoring each PET tray category accordingly. The results are listed in Table S6.

Besides the score per PET tray category, also a three-level assessment is given for each PET tray category with respect to the general compatibility with PET recycling as described in the DfR guidelines, see Table 3.

Based on the criteria defined for the recyclability assessment, and on the average characteristics of the packages in each category, the categories of PET trays were assigned as follows: 1. High compatibility to mechanical recycling: categories 2, 3, 5 and 11 are constituted by packaging for previous food use, characterized by PET content higher than 98 %; transparent colour; low content of product residues; absence of barrier and ink on the tray; absence of adhesive and/or removable adhesive for the closure application system; 2. Medium compatibility to mechanical recycling: categories 3a, 3b, 4, 8, 9 and 10 are constituted by packaging characterised by PET content higher than 93 %; transparent colour; low content of product residue; the presence of PE barrier with content lower than 5 %; the presence of removable adhesive for labels and the closure application system; 3. Low compatibility to mechanical recycling: 1, 1a, 1b, 5a, 5b, 5c, 6, 7, 11a and 12 are constituted by food grade and other types of packaging, characterised by PET content lower than 93 %; transparent, coloured, and opaque trays; high content of product residues; the presence of PE barrier with content higher than 5 %; the presence of non-removable adhesive for labels, closure application system, and pads. Unfortunately, the largest quantities of PET trays correspond also to those with the lowest degree of recyclability through the mechanical process (see Figure 5a). The same evaluation was executed for chemical recycling processes to produce food-grade transparent recycled PET from PET trays, see Table S7.

Based on the criteria defined for the chemical recyclability assessment, and on the average characteristics of the packages in each category, the PET tray categories were assigned as follows: *High compatibility*: categories 2, 3, 3a, 3b, 5 and 11 are constituted by packaging constituted of PET content higher than 50 %; transparent colour; absence of barrier layers and prints on the tray; absence of adhesive and/or removable adhesive for the closure application system; *Medium compatibility*: categories 1, 1a, 1b, 4, 5a, 5b, 5c, 6, 7, 8, 9, 11a and 12 are constituted of PET content higher than 50 %; transparent or coloured trays; the acceptable presence of PE sealing layers; presence of prints and ink on the main body of the package; the presence of adhesive for labels, the closure application system and pads constituted by non-depolymerisable polymers; *Low compatibility*: the packaging waste analysed did not present any characteristics not suitable for chemical recycling, for instance due to the presence of other depolymerisable polymers or a share of PET that is below 50 %.

The suitability of the SP PET trays for depolymerisation processes is most likely high (as shown in Figure 5b), as the accessibility of the PET is high (most multi-layered structures in the SP have PET on the outside), the PET concentration of the SP is high (namely 79 ± 15 %) and the concentration of potentially interfering polymers (other polyesters and polyamides) is likely to be low (at least below 1.8 ± 1.1 %). The only substances present in the SP that could retard or complicate depolymerisation processes are prints and pressure sensitive adhesives (both often based on polyacrylate ester resins), as these will consume reagents and could complicate the separation. Hence depolymerisation processes are potentially good candidate processes to convert SP PET trays into food-grade, transparent recycled PET. Chemical depolymerisation of PET can be performed by various methods (e.g. hydrolysis, methanolysis, glycolysis and aminolysis (Crippa and Morico, 2019), and this study confirms that the multi-material PET trays stream is chemically recyclable. For example, Ügdüler (Ügdüler et al., 2021) has already shown that multi-layer PET feedstocks could be chemically recycled by alkaline hydrolysis, which is the method most capable of tolerating highly contaminated feedstock (Sinha et al., 2010), providing lower yields and greater environmental impacts than mono-material flow. Thus, reducing the material composition complexity of the PET trays stream would not only increase recyclability by mechanical technology, but also improve the yields of the chemical process, making it more environmentally sustainable.

Several studies (H. Chen et al., 2021; Li et al., 2022; Tamizhdurai et al., 2024; Yu et al., 2023) indicated depolymerisation as a useful route for multi-material plastics recovery, providing higher yields than mechanical recycling (H. Chen et al., 2021); viceversa other researchers showed that it is limited by its high environmental impact (Gracida-Alvarez et al., 2023) and by the absence of well-developed infrastructure (Bernat, 2023; Jung et al., 2023). Instead, increasing the rate of mechanical recycling could markedly reduce the footprints of the entire cycle. Yet, mechanical recycling needs to be addressed by improved sorting, DfR and new circular business models (Mangold and von Vacano, 2022; Seier et al., 2023). Better packaging design would lead to more pure sorted PET tray streams for mechanical recycling, which if jointly used with chemical recycling could help replace virgin PET manufacture (Vogt et al., 2021), but also to dispose of fewer plastic flows in incineration and landfills, reducing the carbon footprint (Ghosh et al., 2023).

Thus, PET trays need to be redesigned in order to be highly recyclable. As discussed, the impurities in the PET trays feedstock arise both from sorting errors, and from composition of this packaging itself. The complexity of PET trays can largely be attributed to their crucial role in preserving food products. Each layer of the packaging serves a specific purpose in maintaining the functionality of the package (Delva et al., 2019). However, for end-of-life management, the multilayer structure presents challenges in efficiently recovering the entire sorted PET tray waste stream through mechanical recycling. Some design aspects of the PET trays that reduce especially the quality of the mechanically recycled PET can simply be removed, for instance mono-material should be preferred, if multi-material components are indispensable, they should be easy separable and decorations should be designed avoiding excessive inks, coatings and unnecessary attachments (Ding and Zhu, 2023). Since the fast moving consumer good (FMCG) industry often faces dilemmas to change the design aspects of the PET trays that reduce the quality of the mechanically recycled PET. For example, meat companies do want to use PET-PE trays instead of PET-trays with an adhesive on the flange, since it reduces the sealing time (renders a higher production capacity) and reduces the leak chance (and hence forms a lower food safety liability issue (Thoden van Velzen, 2020). In order to ensure the recyclability of the sorted product, it is desirable that the FMCG industry redesigns its packages as much as is possible. DfR strategies has proven instrumental in envisioning new possibilities for multi material plastic packaging (Ghosh et al., 2023; Mangold and von Vacano, 2022; Matos et al., 2024; Venkatachalam et al., 2022; Yu et al., 2023); redesigning would lead to reduce the contamination of the waste streams, improving

Table 3
Design for mechanical and chemical recycling guidelines for the analysed categories.

		HIGH COMPATIBILITY	MEDIUM COMPATIBILITY	LOW COMPATIBILITY
MECHANICAL RECYCLING				
MAIN BODY	*Main constituent polymer (predominant weight)*	≥ 98% PET	98% ≥ PET ≥ 93%	≤ 93%PET
	Colour	Transparent	Transparent	Transparent, opaque, coloured
	Barrier	Not present	< 5 % PE	≥ 5 % PE
CLOSURE SYSTEM	*Material*	PE, PP, Paper	Multi-components (PE, PP, PVC, paper, metals)	Multi-components and printed lidding films
	Adhesives	Not present	Hotmelt adhesive at the leading and trailing edges	Not-removable hotmelt adhesive at the leading and trailing edges
	Sortability	High	Low	Low
DECORATION	*Labels*	Paper, PE, PP, other plastics	Paper, PE, PP, other plastics	Paper, PE, PP, other plastics, metals
	Adhesives (for labels and other components)	Not present	Present	Present
	Ink	Not-present	Present	Present
	Package use	Food	Food, Non- food	Food, Non-food
	Other components (Soaker or bubble pads)	Not present	Present	Present
	PET-tray categories	2, 3, 5, 11	3a, 3b, 4, 8, 9, 10	1, 1a, 1b, 5a, 5b, 5c, 6, 7, 11a,12
	Weight (%) in sorted products	27%	14%	60%
CHEMICAL RECYCLING				
MAIN BODY	*Main body composition*	PET	PET, PE	< 50% PET, Depolymerisable polymers (e.g. PA)
	Color	Transparent	Transparent, opaque, coloured	Transparent, opaque, coloured
SUBCOMPONENTS	*Top film, label, absorber pad*	PE, PP, Paper, non-depolymerisable polymers	PE, PP, Paper, non-depolymerisable polymers	Depolymerisable polymers (e.g. PA)
	Adhesives (for top films, labels and other components)	Not present	PSA	Hotmelt adhesives, Depolymerisable polymers (e.g. PA)
	Ink	Not present	Present on the main body	Present on the main body
	Sortability	High	Low	Low
	PET-tray categories	2, 3, 3a, 3b, 5, 11	1, 1a, 1b, 4, 5a, 5b, 5c, 6, 7, 8, 9, 10,11a, 12	/
	Weight (%) in sorted products	28 %	72 %	0 %

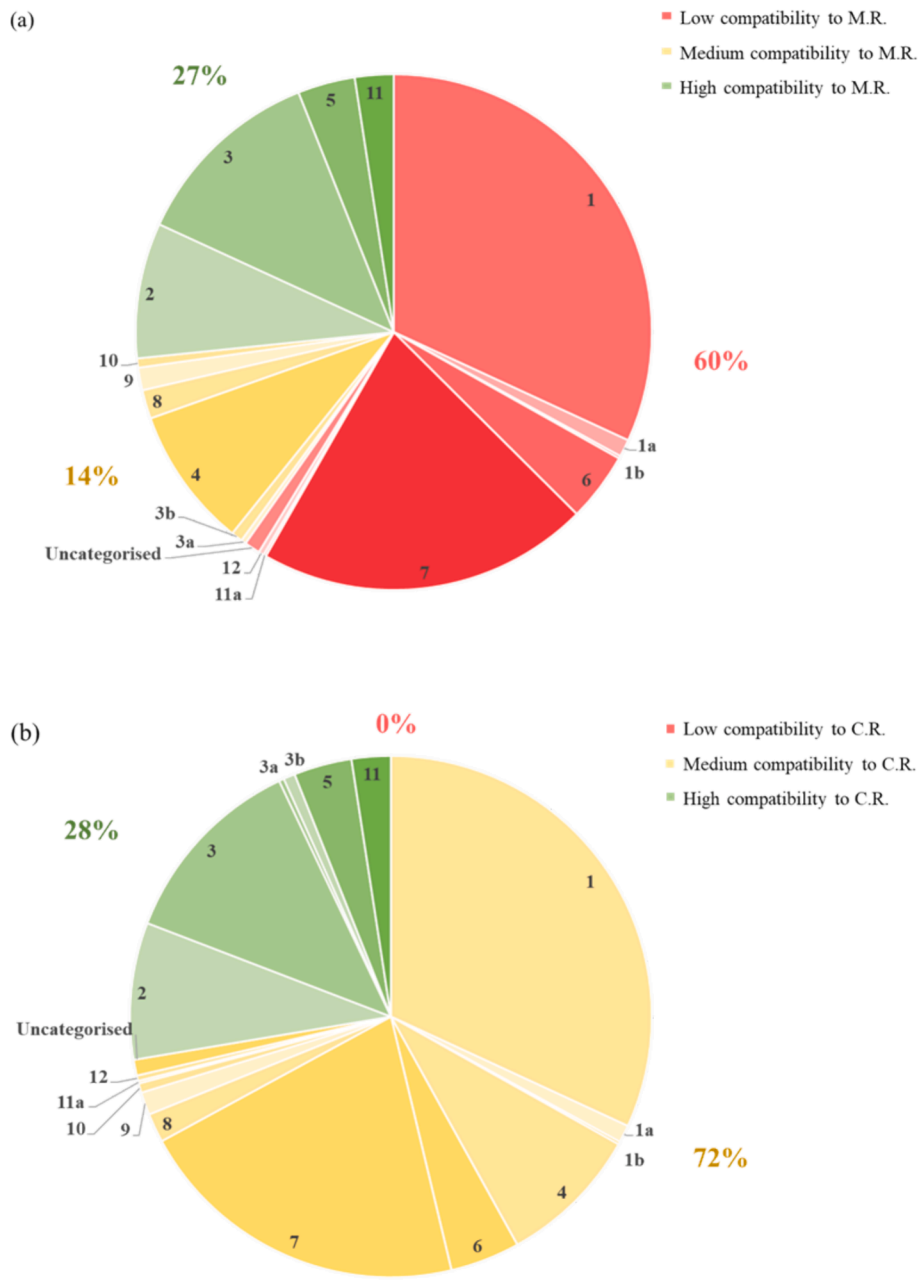

Fig. 5. Weight percentage per category found in sorted product samples (sample 3 and 4) and colour classification in low, medium and high compatibility to a) mechanical recycling (M.R.) and b) chemical recycling (C.R.).

the quality and yields of the obtained rPET and increasing the PET recycling rates (Roosen, 2020).

4. Conclusions

Polyethylene terephthalate (PET) is one of the favoured candidate polymers for closed-loop recycling for new packaging applications. However, the mechanical recycling of thermoformed PET packaging, specifically PET trays, remains challenging. The urge to recycle PET trays is large in Europe, but especially in the Netherlands where it is the most abundant plastic packaging type in the LWP and the legal recycling targets are ambitious.

Sixteen different types of PET trays are used in the Netherlands to package different food products ranging from meat, fish, cheese, salads, humus, yoghurt, peanut butter and even a few non-food articles. These different categories of PET trays are not only used to package different products, they also have different material composition. These range from a simple clamshell of PET for grapes (with only a single label of PP and PSA as non-PET component) to meat packages that are composed of seven components and more than 6 different materials.

PET trays are collected with the LWP in the Netherlands and sorting facilities direct them towards the SP named “PET trays”. The composition of this SP has been studied and was found to be heterogeneous, in terms of packaging elements, polymers and contaminants present in the stream. Furthermore, most PET trays are heavily soiled, deformed and were found to have lost one or more components such as top-films, labels, absorbers.

The material composition of all sixteen categories of PET trays were compared to common DfR guidelines and the designs of the majority of the PET trays were found to converse with these guidelines. Hence, the majority of the PET trays in the SP are not designed for closed-loop mechanical recycling and FMCG industries experience dilemmas in

altering these packaging designs. It will therefore remain extremely challenging to produce food-grade, transparent recycled PET from this feedstock with mechanical recycling. Depolymerisation processes hold more promise as the PET in these trays is easily accessible, the PET concentration in the SP feedstock is 79 ± 15 % and there are hardly any interfering polymers present in this feedstock.

At the end, it can be said that the useful strategy to improve the circularity of non-bottle PET packaging waste is based on the redesign of PET tray packages, with the aim of enhancing mechanical and also chemical recyclability, increasing recycling rates and the quality of final recycling, as well as helping to reduce process losses along the value chain as well as environmental impacts related to the entire life cycle.

Hence, close the PET tray loop requires collaboration across all the value chain, manufacturers should increasingly adhere to these guidelines, and retailers involved in the use of packaging for their products should be engaged to ensure its end-of-life valorisation without implications for their food-product properties, finally, also consumers must be willing to trade product aesthetic for sustainability.

CRediT authorship contribution statement

Giusy Santomasi: Conceptualization, Data curation, Formal analysis, Investigation, Visualization, Writing – original draft. **Rosiana Aquilino:** Investigation, Visualization. **Marieke Brouwer:** Data curation, Validation, Writing – original draft. **Sabino De Gisi:** Writing – review & editing. **Ingeborg Smeding:** Funding acquisition, Project administration, Writing – review & editing. **Francesco Todaro:** Conceptualization, Supervision, Writing – review & editing. **Michele Notarnicola:** Resources, Supervision, Writing – review & editing. **Eggo U. Thoden van Velzen:** Conceptualization, Data curation, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Eggo U. Thoden van Velzen reports financial support was provided by Institute for Sustainable Process Technology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper].

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2024.06.016.

References

Abedsoltan, H., 2023. A focused review on recycling and hydrolysis techniques of polyethylene terephthalate. Polym Eng Sci. https://doi.org/10.1002/pen.26406.
Agostini, I., Ciuffi, B., Gallorini, R., Rizzo, A.M., Chiaramonti, D., Rosi, L., 2022. Recovery of terephthalic acid from densified post-consumer plastic Mix by HTL process. Molecules 27, 7112. https://doi.org/10.3390/molecules2720711.
Antonopoulos, I., Faraca, G., Tonini, D., 2021. Recycling of post-consumer plastic packaging waste in EU: Process efficiencies, material flows, and barriers. Waste Manag. 126, 694–705. https://doi.org/10.1016/j.wasman.2021.04.002.
Barthélémy, E., Spyropoulos, D., Milana, M.R., Pfaff, K., Gontard, N., Lampi, E., Castle, L., 2014. Safety evaluation of mechanical recycling processes used to produce polyethylene terephthalate (PET) intended for food contact applications. Food Additives and Contaminants - Part A 31, 490–497. https://doi.org/10.1080/19440049.2013.871755.
Baskaran, S., Sathiavelu, M., 2020. Application of Attenuated Total Reflection - Fourier Transform Infrared spectroscopy to characterize the degradation of littered multilayer food packaging plastics. Vib Spectrosc 109. https://doi.org/10.1016/j.vibspec.2020.103105.
Bernat, K., 2023. Post-consumer plastic waste management: from collection and sortation to mechanical recycling. Energies (basel). https://doi.org/10.3390/en16083504.
Brouwer, M., Thoden van Velzen, E.U., Augustinus, A., Soethoudt, H., De Meester, S., Ragaert, K., 2018. Predictive model for the Dutch post-consumer plastic packaging recycling system and implications for the circular economy. Waste Manag. 71, 62–85. https://doi.org/10.1016/j.wasman.2017.10.034.
Brouwer, M., Picuno, C., Thoden van Velzen, E.U., Kuchta, K., de Meester, S., Ragaert, K., 2019. The impact of collection portfolio expansion on key performance indicators of the Dutch recycling system for Post-Consumer Plastic Packaging Waste, a comparison between 2014 and 2017. Waste Manag. 100, 112–121. https://doi.org/10.1016/j.wasman.2019.09.012.
Brouwer, M., Picuno, C., Thoden van Velzen, E.U., Kuchta, K., de Meester, S., Ragaert, K., 2019. The impact of collection portfolio expansion on key performance indicators of the Dutch recycling system for Post-Consumer Plastic Packaging Waste, a comparison between 2014 and 2017. Waste Manag. 100, 112–121. https://doi.org/10.1016/j.wasman.2019.09.012.
Brouwer, M.T., van Velzen, E.U.T., Ragaert, K., Klooster, R.T., 2020. Technical limits in circularity for plastic packages. Sustainability (switzerland) 12, 1–29. https://doi.org/10.3390/su12310021.
Carte, T.L., Moet, A., 1993. Morphological origin of super toughness in poly (ethylene Terephthalate)/ polyethylene blends. J Appl Polym Sci 48.
Chen, X., Kroell, N., Wickel, J., Feil, A., 2021b. Determining the composition of post-consumer flexible multilayer plastic packaging with near-infrared spectroscopy. Waste Manag. 123, 33–41. https://doi.org/10.1016/j.wasman.2021.01.015.
Chen, H., Wan, K., Zhang, Y., Wang, Y., 2021a. Waste to wealth: Chemical recycling and chemical upcycling of waste plastics for a great future. ChemSusChem. https://doi.org/10.1002/cssc.202100652.
Cirrec, 2023. Van tray naar tray met rPET van Cirrec https://www.verpakkingsmanagement.nl/duurzame-verpakkingen/van-tray-naar-tray-met-rpet-van-cirrec (accessed 09 May 2023).
Crippa, M., Morico, B., 2019. PET depolymerization: A novel process for plastic waste chemical recycling. Stud Surf Sci Catal 179, 215–229. https://doi.org/10.1016/B978-0-444-64337-7.00012-4.
Delva, L., Deceur, C., Van Damme, N., Ragaert, K., 2019. Compatibilization of PET-PE blends for the recycling of multilayer packaging foils, in: AIP Conference Proceedings. American Institute of Physics Inc. doi: 10.1063/1.5084815.
Ding, Q., Zhu, H., 2023. The key to solving plastic packaging wastes: Design for recycling and recycling technology. Polymers (basel). https://doi.org/10.3390/polym15061485.
Ellen MacArthur Foundation, 2023. The global commitment 2023 progress report. https://www.ellenmacarthurfoundation.org/global-commitment-2023/overview.
Eriksen, M.K., Astrup, T.F., 2019. Characterisation of source-separated, rigid plastic waste and evaluation of recycling initiatives: Effects of product design and source-separation system. Waste Manag. 87, 161–172. https://doi.org/10.1016/j.wasman.2019.02.006.
Eunomia, 2022. PET market in Europe: State of the play 2022, production, collection and recycling. https://petcore-europe.org/news-events/409-pet-market-in-europe-state-of-play-2022.html.
European Commission, 2018. A European Strategy for Plastics in a Circular Economy. January 16th 2018, Brussels.
European Parliament and Council, 2019. Directive 2019/904 on the impact of certain plastic products on the environment. Official Journal of the Europe Union L155/1, 1–19. June 5th 2019, Brussels.
Faerch group, 2023. Cirrec website. https://www.cirrec.nl/ (accessed 09 May 2023).
Feil, A., Coskun, E., Bosling, M., Kaufeld, S., Pretz, T., 2019. Improvement of the recycling of plastics in lightweight packaging treatment plants by a process control concept. Waste Manag. Res. 37, 120–126. https://doi.org/10.1177/0734242X19826372.
Fitaroni, L.B., de Oliveira, É.C., Marcomini, A.L., Paranhos, C.M., Freitas, F.L., Cruz, S.A., 2020. Reprocessing and solid state polymerization on contaminated post-consumer PET: Thermal and crystallization behavior. J Polym Environ 28, 91–99. https://doi.org/10.1007/s10924-019-01579-9.
Franz, R., Mauer, A., Welle, F., 2004. European survey on post-consumer poly(ethylene terephthalate) (PET) materials to determine contamination levels and maximum consumer exposure from food packages made from recycled PET. Food Addit Contam 21, 265–286. https://doi.org/10.1080/02652030310001655489.

Franz, R., Welle, F., 2002. Recycled poly(ethylene terephthalate) for direct food contact applications: Challenge test of an inline recycling process. Food Addit Contam 19, 502–511. https://doi.org/10.1080/02652030110102845.
Franz, R., Welle, F., 2020. Contamination levels in recollected PET bottles from non-food applications and their impact on the safety of recycled pet for food contact. Molecules 25. https://doi.org/10.3390/molecules25214998.
Gadaleta, G., De Gisi, S., Todaro, F., D'Alessandro, G., Binetti, S., Notarnicola, M., 2023. Assessing the sorting efficiency of plastic packaging waste in an italian material recovery facility: Current and upgraded configuration. Recycling 8. https://doi.org/10.3390/recycling8010025.
Geueke, B., Groh, K., Muncke, J., 2018. Food packaging in the circular economy: Overview of chemical safety aspects for commonly used materials. J Clean Prod. https://doi.org/10.1016/j.jclepro.2018.05.005.
Ghosh, T., Avery, G., Bhatt, A., Uekert, T., Walzberg, J., Carpenter, A., 2023. Towards a circular economy for PET bottle resin using a system dynamics inspired material flow model. J Clean Prod 383. https://doi.org/10.1016/j.jclepro.2022.135208.
Gracida-Alvarez, U.R., Xu, H., Benavides, P.T., Wang, M., Hawkins, T.R., 2023. Circular economy sustainability analysis framework for plastics: Application for poly (ethylene Terephthalate) (PET). ACS Sustain Chem Eng 11, 514–524. https://doi.org/10.1021/acssuschemeng.2c04626.
Gruene Punkt, 2023. Gruener Punkt - Website. https://www.gruener-punkt.de/en/downloads (Accessed 09 May 2023).
He, J.J., Gilpatrick, B., 1999. Applications of DSC in conjunction with FTIR in plastic identification. CRC Press LLC., Boca Raton, FL, pp. 2314–2318.
ICIS, Independent Commodity Intelligence Services, 2024. PET Market in Europe: State of play, production, collection and recycling data 2022. https://www.icis.com/explore/resources/pet-market-state-of-play-2022/ (accessed 24 April 2024).
Jansen, M., Thoden van Velzen, E.U., Pretz, Th., 2015. Handbook for sorting of plastic packaging waste concentrates: separation efficiencies of common plastic packaging objects in widely used separation machines at existing sorting facilities with mixed postconsumer plastic packaging waste as input. FBR report 1604. Wageningen UR Food & Biobased Research. https://edepot.wur.nl/362985.
Jung, H., Shin, G., Kwak, H., Hao, L.T., Jegal, J., Kim, H.J., Jeon, H., Park, J., Oh, D.X., 2023. Review of polymer technologies for improving the recycling and upcycling efficiency of plastic waste. Chemosphere. https://doi.org/10.1016/j.chemosphere.2023.138089.
Kahlert, S., Bening, C.R., Kahlert, S., 2022. Why pledges alone will not get plastics recycled: Comparing recyclate production and anticipated demand. Resour. Conserv. Recycl. 181, 106279 https://doi.org/10.3929/ethz-b-000537561.
Karayannidis, G.P., Achilias, D.S., 2007. Chemical recycling of poly(ethylene terephthalate). Macromol Mater Eng 292, 128–146. https://doi.org/10.1002/mame.200600341.
Kroell, N., Chen, X., Küppers, B., Lorenzo, J., Maghmoumi, A., Schlaak, M., Thor, E., Nordmann, C., Greiff, K., 2023. Near-infrared-based determination of mass-based material flow compositions in mechanical recycling of post-consumer plastics: Technical feasibility enables novel applications. Resour Conserv Recycl 191. https://doi.org/10.1016/j.resconrec.2023.106873.
Lange, J.P., 2021. Managing plastic waste-sorting, recycling, disposal, and product redesign. ACS Sustain Chem Eng. https://doi.org/10.1021/acssuschemeng.1c05013.
Li, H., Aguirre-Villegas, H.A., Allen, R.D., Bai, X., Benson, C.H., Beckham, G.T., Bradshaw, S.L., Brown, J.L., Brown, R.C., Cecon, V.S., Curley, J.B., Curtzwiler, G.W., Dong, S., Gaddameedi, S., García, J.E., Hermans, I., Kim, M.S., Ma, J., Mark, L.O., Mavrikakis, M., Olafasakin, O.O., Osswald, T.A., Papanikolaou, K.G., Radhakrishnan, H., Sanchez Castillo, M.A., Sánchez-Rivera, K.L., Tumu, K.N., Van Lehn, R.C., Vorst, K.L., Wright, M.M., Wu, J., Zavala, V.M., Zhou, P., Huber, G.W., 2022. Expanding plastics recycling technologies: chemical aspects, technology status and challenges. Green Chem. https://doi.org/10.1039/d2gc02588d.
Lybaek, R., 2024. Opportunity analysis for re-cycling household plastic wastes in denmark-exploratory case study and future outlook. Rikke Lybaek / GMSARN International Journal 8, 385–391.
Mangold, H., von Vacano, B., 2022. The frontier of plastics recycling: rethinking waste as a resource for high-value applications. Macromol Chem Phys 223. https://doi.org/10.1002/macp.202100488.
Matos, J., Martins, C.I., Simoes, R., 2024. Circularity micro-indicators for plastic packaging and their relation to circular economy principles and design tools. Sustainability (switzerland) 16. https://doi.org/10.3390/su16052182.
PETCORE Europe, 2020. Design for recycling guidelines PET Trays clear transparent. https://www.petcore-europe.org/images/Design-for-Recycling-Guidelines-PET-Thermoforming-Trays-nov2018.pdf (accessed 24 April 2024).
Picuno, C., Alassali, A., Chong, Z.K., Kuchta, K., 2021. Flows of post-consumer plastic packaging in Germany: An MFA-aided case study. Resour Conserv Recycl 169. https://doi.org/10.1016/j.resconrec.2021.105515.
Quicker, P., Seitz, M., Vogel, J., 2022. Chemical recycling: A critical assessment of potential process approaches. Waste Manag. Res. 40, 1494–1504.
Recyclass, 2021. Transparent Clear Thermoforming Mono PET. https://recyclass.eu/guidelines/clear-pet-thermoforming-trays/ (accessed 24 April 24).
Roosen, M., Mys, N., Kusenberg, M., Billen, P., Dumoulin, A., Dewulf, J., Van Geem, K. M., Ragaert, K., De Meester, S., 2020b. A detailed analysis of the composition of selected plastic packaging waste products and its implications for mechanical and thermochemical recycling (Supporting information).
Roosen, M., Mys, N., Kusenberg, M., Billen, P., Dumoulin, A., Dewulf, J., Van Geem, K. M., Ragaert, K., De Meester, S., 2020. Detailed analysis of the composition of selected plastic packaging waste products and its implications for mechanical and thermochemical recycling. Environ Sci Technol 54, 13282–13293. https://doi.org/10.1021/acs.est.0c03371.
Schyns, Z.O.G., Shaver, M.P., 2021. Mechanical recycling of packaging plastics: A review. Macromol Rapid Commun. https://doi.org/10.1002/marc.202000415.
Seier, M., Archodoulaki, V.M., Koch, T., Duscher, B., Gahleitner, M., 2022. Polyethylene terephthalate based multilayer food packaging: Deterioration effects during mechanical recycling. Food Packag Shelf Life 33. https://doi.org/10.1016/j.fpsl.2022.100890.
Seier, M., Roitner, J., Archodoulaki, V.M., Jones, M.P., 2023. Design from recycling: Overcoming barriers in regranulate use in a circular economy. Resour Conserv Recycl 196. https://doi.org/10.1016/j.resconrec.2023.107052.
Silva, S.M., Medeiros, E.S., Galvão, L.S., Santos, A.S.F., 2023. Characterization of adhesive content in post-consumer poly(ethylene terephthalate) bottles and assessment of its impact on poly(ethylene terephthalate) recyclability. Prog. Rubber Plast. Recycl. Technol. https://doi.org/10.1177/14777606231152507.
Sinha, V., Patel, M.R., Patel, J.V., 2010. Pet waste management by chemical recycling: A review. J Polym Environ. https://doi.org/10.1007/s10924-008-0106-7.
Solis, M., Silveira, S., 2020. Technologies for chemical recycling of household plastics – A technical review and TRL assessment. Waste Manag. https://doi.org/10.1016/j.wasman.2020.01.038.
Souder, J., Kennedy, E., Xu, C., Gruber, B., Paes, C., Hu, R., Vazquez Bustelo, J., Kamps, M., Sierra Garcia, M., Björk, C. and Amadei, A.M., Modelling plastic product flows and recycling in the EU. Publications Office of the European Union. JRC, 135901 https://doi:10.2760/69492.
Spaseska, D., Civkaroska, M., 2010. Alkaline hydrolysis of poly(ethylene terephthalate) recycled from the post-consumer soft-drink bottles. Journal of the University of Chemical Technology and Metallurgy 45 (4), 379–384. https://journal.uctm.edu/node/j2010-4/2_Spaseska_379-384.pdf.
Staatssecretaris, 2014. Staatssecretaris van Infrastructuur & Waterstaat. 2014. Besluit beheer verpakkingen. Staatsblad van het Koninkrijk der Nederlanden. 27 oktober 2014, nr. 409.
Staatssecretaris, 2022. Staatssecretaris van Infrastructuur & Waterstaat. 2022. Regeling kunststofproducten voor eenmalig gebruik. Staatscourant 29 maart 2022, nr. 8376.
Tamizhdurai, P., Mangesh, V.L., Santhosh, S., Vedavalli, R., Kavitha, C., Bhutto, J.K., Alreshidi, M.A., Yadav, K.K., Kumaran, R., 2024. A state-of-the-art review of multilayer packaging recycling: Challenges, alternatives, and outlook. J Clean Prod. https://doi.org/10.1016/j.jclepro.2024.141403.
Thoden van Velzen, E.U., 2020. Seeking circularity: Finding sustainable packaging solutions for fresh products. Wageningen UR Food & Biobased Research, 10.18174/526932 FBR report 2068.
Thoden van Velzen, E.U., Brouwer, M.T., 2014. Samenstelling van gescheiden ingezamelde kunststofverpakkingen. Wageningen UR Food & Biobased Research. FBR report 1487.
Thoden van Velzen, E.U., Linnemann, A.R., 2008. Modified atmosphere packaging of fresh meats - Sudden partial adaptation caused an increase in sustainability of Dutch supply chains of fresh meats. Packag. Technol. Sci. 21, 37–46. https://doi.org/10.1002/pts.776.
Thoden van Velzen, E.U., Brouwer, M.T., Huremovic, D., 2018. Sorting protocol for packaging wastes. Wageningen UR Food & Biobased Research, 10.18174/451703 FBR report 1826.
Thoden van Velzen, E.U., Brouwer, M.T., Feil, A., 2019. Collection behaviour of lightweight packaging waste by individual households and implications for the analysis of collection schemes. Waste Manag. 89, 284–293. https://doi.org/10.1016/j.wasman.2019.04.021.
Thoden van Velzen, E.U., Smeding, I.W., Molenveld, K., 2020. Verkenning maximaal haalbarekwaliteiten gerecyclede PET uit schalen: Praktische studie naar de maximaal haalbare kwaliteit van mechanisch gerecyclede PET uitschalen. Wageningen UR Food & Biobased Research, 10.18174/526914 FBR report 2069.
Trossaert, L., De Vel, M., Cardon, L., Edeleva, M., 2022. Lifting the sustainability of modified PET-based multilayer packaging material with enhanced mechanical recycling potential and processing. Polymers (basel) 14. https://doi.org/10.3390/polym14010196.
Uehara, G.A., França, M.P., Canevarolo Junior, S.V., 2015. Recycling assessment of multilayer flexible packaging films using design of experiments. Polimeros 25, 371–381. https://doi.org/10.1590/0104-1428.1965.
Ügdüler, S., Van Geem, K.M., Denolf, R., Roosen, M., Mys, N., Ragaert, K., De Meester, S., 2020. Towards closed-loop recycling of multilayer and coloured PET plastic waste by alkaline hydrolysis. Green Chem. 22, 5376–5394. https://doi.org/10.1039/d0gc00894j.
Ügdüler, S., De Somer, T., Van Geem, K.M., Roosen, M., Kulawig, A., Leineweber, R., De Meester, S., 2021. Towards a better understanding of delamination of multilayer flexible packaging films by carboxylic acids. Chem Sus Chem 14, 4198–4213. https://doi.org/10.1002/cssc.202002877.
Venkatachalam, V., Pohler, M., Spierling, S., Nickel, L., Barner, L., Endres, H.J., 2022. Design for recycling strategies based on the life cycle assessment and end of life options of plastics in a circular economy. Macromol Chem Phys 223. https://doi.org/10.1002/macp.202200046.
Vogt, B.D., Stokes, K.K., Kumar, S.K., 2021. Why is recycling of postconsumer plastics so challenging? ACS Applied Polymer Materials. 3, 4325–4346. https://doi.org/10.1021/acsapm.1c00648.
Vollmer, I., Jenks, M.J.F., Roelands, M.C.P., White, R.J., van Harmelen, T., de Wild, P., van der Laan, G.P., Meirer, F., Keurentjes, J.T.F., Weckhuysen, B.M., 2020. Beyond mechanical recycling: Giving new life to plastic waste. Angewandte Chemie - International Edition. https://doi.org/10.1002/anie.201915651.
Volmajer Valh, J., Stopar, D., Selaya Berodia, I., Erjavec, A., Šauperl, O., Fras Zemljič, L., 2022. Economical chemical recycling of complex PET waste in the form of active packaging material. Polymers (basel) 14. https://doi.org/10.3390/polym14163244.

Watkins, E., Romagnoli, V., Kirhensteine, I., Ruckley, F., Kreibig, J., Mitsios, A., Pantzar, M., Garbarino, E., Saveyn, H., 2020. Support to the Circular Plastics Alliance in establishing a work plan to develop guidelines and standards on design-for-recycling of plastic products. Publications Office of European Union. https://doi.org/10.2760/936397.

Welle, F., 2008. Decontamination efficiency of a new post-consumer poly(ethylene terephthalate) (PET) recycling concept. Food Addit Contam Part A Chem Anal Control Expo Risk Assess 25, 123–131. https://doi.org/10.1080/02652030701474227.

Welle, F., 2014. Simulation of the decontamination efficiency of PET recycling processes based on solid-state polycondensation. Packag. Technol. Sci. 27, 141–148. https://doi.org/10.1002/pts.2013.

Zhou, G., Gu, Y., Wu, Y., Gong, Y., Mu, X., Han, H., Chang, T., 2020. A systematic review of the deposit-refund system for beverage packaging: Operating mode, key parameter and development trend. J Clean Prod 251, 119660. https://doi.org/10.1016/J.JCLEPRO.2019.119660.