



The impact of sorting quality on the properties of recycled flexible plastic packaging

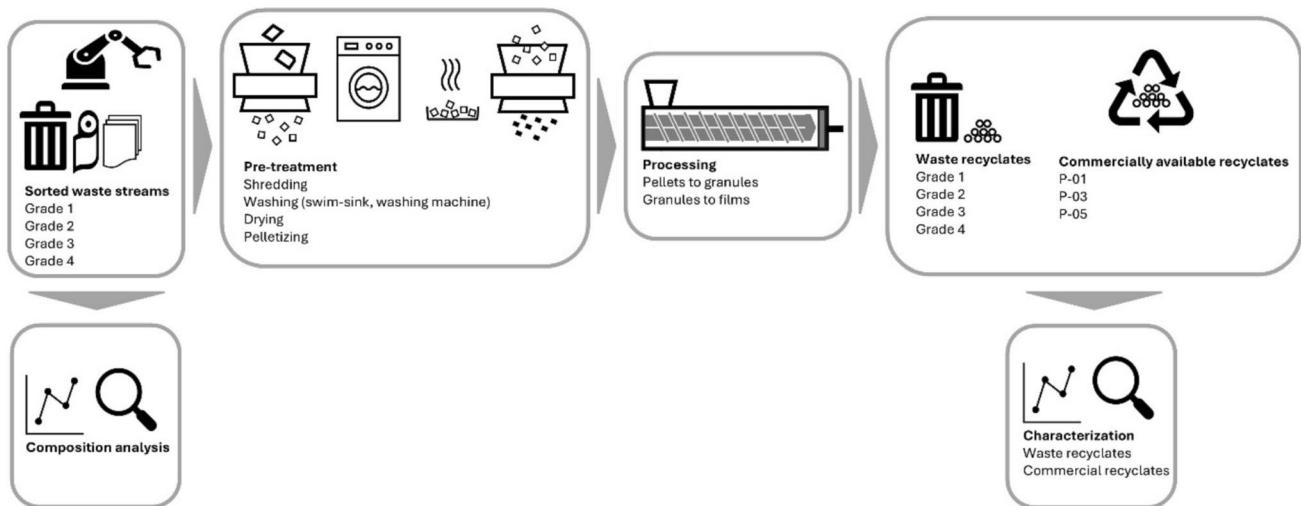
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Abstract

Sorting is crucial for the recyclability of plastic packaging waste, yet flexible packaging poses challenges due to factors like low film mass, color variations, and multi-layer structures. This study assessed the impact of sorting quality on recyclate properties by analyzing four sorting grades. Grade 1 was compiled based on the composition of commercial wastes in Upper Austria. Composition analysis showed that Grades 2 and 3 had high polyethylene (PE) film content (87.1% and 84.0%, respectively), while Grade 4 had significantly less (59.6%) and higher contamination levels (23.2% vs. 7.0% in Grade 2). Mechanical recycling and characterization revealed that better sorting improved recyclate properties. Oxidation onset temperature (OOT) remained stable across Grades 1 to 4. Density decreased from Grade 1 to Grade 4. Transparency declined with increasing contamination, with Grade 4 exhibiting 3,510 inclusions/m² compared to 250 inclusions/m² in Grade 1. Mechanical properties, such as strain and stress, also decreased from Grade 1 to Grade 4, as larger inclusions (300–599 μm) in poorly sorted grades disrupted the polymer matrix and reduced tensile strength. Comparisons with three commercial recyclates highlighted the superior quality of well-sorted materials. This study demonstrates that improved sorting enhances recyclate quality, emphasizing the need for advancements in sorting technologies, optimized waste collection systems, and increased market demand for recyclates to support a circular economy.

Graphical abstract



Extended author information available on the last page of the article

Introduction

Plastic waste can be recycled through various processes and further transformed into numerous products. However, secondary raw materials derived from recycled plastics often face significant market challenges. One notable issue is the overproduction of virgin plastic materials, particularly in Asia and North America, which leads to an oversupply in the European market. Virgin plastic materials are typically favored due to their consistent properties and low prices. While recycled materials are often more affordable, their quality can fluctuate, and prices depend on the availability of waste streams and the additional treatment steps required to achieve comparable (Torkelis et al. 2024) quality. Consequently, virgin plastics remain the preferred choice in many applications.

To address these challenges, the European Union (EU) has initiated a strategic shift toward sustainability through the European Green Deal. The primary goal of the Green Deal is to achieve climate neutrality by 2050, aligning with the EU's commitments under the Paris Agreement. This strategy encompasses a broad range of policy initiatives targeting key economic sectors such as energy, transportation, industry, agriculture, and sustainable finance (European Council of the European Union, European Green Deal. [Online]. Available: <https://www.consilium.europa.eu/en/policies/green-deal/> (accessed: Feb. 3 2025) 2025).

A critical component of the Green Deal is the Circular Economy Action Plan, which outlines over 30 actions to promote the development of sustainable products, enhance circularity in production processes, empower consumers, and reduce waste generation (World Business Council for Sustainable Development 2020; Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions 2020; Circular economy 2025). To guide member states along this path, the EU has established several directives and regulations specific to plastic waste management. Key legislative acts include:

- The Waste Framework Directive (Directive 2008/98/EC of the European Parliament and of the Council of 19 2008)
- The Packaging and Packaging Waste Directive (Parliament et al. 1994), which got replaced by the Packaging and Packaging Waste Regulation in December 2024 (Regulation (EU) 2025/40 of the European Parliament and of the Council of 19 2025)
- The Single-Use Plastics Directive (Directive (EU) 2019/904 of the European Parliament and of the Council of 5 2019)

The Waste Framework Directive establishes the legal framework for handling waste within the EU and aims to reduce environmental and health impacts while promoting the transition to a circular economy (Commission and Directive 2025). The Packaging and Packaging Waste Regulation establishes key measures to reduce waste and increase recycling, including a waste reduction by 2030, a reduction in packaging waste per capita by 5%, with further reductions of 10% by 2035 and 15% by 2040. The regulation stipulates that all packaging must be recyclable by 2030, with large-scale recycling mandatory by 2035. Extended Producer Responsibility (EPR) fees will be applied based on recyclability. Minimum recycled content targets for plastic packaging by 2030 include 30% for PET beverage bottles, 10% for other contact-sensitive plastics, and 35% for other plastic packaging, with higher targets set for 2040. Further measures include reuse and refill targets, packaging restrictions on miniature cosmetics and fresh produce, mandatory labeling, and stricter regulations concerning environmental claims to ensure accuracy and transparency (Ltd 2025). The Single-Use Plastics Directive mandates substituting single-use products with more sustainable alternatives. Achieving these goals necessitates improvements in collection and sorting systems. Without adequate collection and sorting, recyclable materials are lost, precluding the opportunity to increase recycling rates (Eygen et al. 2018). Research by Antonopoulos et al. (Antonopoulos et al. 2021) highlights substantial material losses during the sorting and recycling stages of waste processing in the EU. For instance, the sorting rate for flexible films varied between 55% and 89%. To achieve a 55% recycling rate, a sorting rate of at least 80% is necessary. In Austria, van Eygen et al. (Eygen et al. 2018) emphasized the importance of sorting in determining the end-of-life solutions for flexible film packaging. These solutions include landfill, energy recovery, and recycling, with the latter subdivided into chemical and mechanical recycling (Rudolph et al. 2020). Chemical recycling is the process of breaking down macromolecules into monomers or oligomers, which can subsequently be reused (Martens and Goldmann 2016). However, not all waste streams can be directly processed in chemical reactors, necessitating meticulous sorting to remove contaminants and interfering materials (Cagnetta et al. 2018). Mechanical recycling, on the other hand, preserves the original polymer structure but requires sorted waste streams to ensure the quality of the recycled material (Al-Salem et al. 2009; Ragaert et al. 2017). Therefore, both chemical and mechanical recycling warrant sorting processes to ensure efficiency and effectiveness.

Typical sorting processes in recycling facilities involve several steps, including manual pre-sorting, direct and indirect sorting mechanisms, whereas direct sorting utilizes physical properties such as density, size, and/or magnetism. Indirect sorting utilizes sensor-based methods such as

near-infrared spectroscopy or X-ray measurements (Ragaert et al. 2017; Europe and “Guidance on Quality Sorting of Plastic Packaging”, 2019).

In the context of the sorting process for flexible films, the fundamental principles remain the same; however, certain challenges arise due to the low mass of these materials. Wind shifters have been found to be effective in the separation of two-dimensional (2D) and three-dimensional (3D) fractions. However, the sorting of small films poses a significant challenge due to their tendency to become airborne, resulting from their high volume-to-weight ratio (C. T. d. M. Soares et al. 2022; Schyns and Shaver 2021). Despite these challenges, alternative sorting methods, such as swim-sink density separation, have proven effective for flexible films (Wijdeveld 2015). Manual sorting at the initial stage of the sorting process has been shown to enhance both recovery efficiency and purity levels of sorted films (Antonopoulos et al. 2021). While near-infrared (NIR) sorting is a promising technology for the separation of flexible films, certain limitations persist. Specifically, the presence of thin coating layers and black-colored materials poses significant challenges in the detection process. Furthermore, multi-layer films present an additional difficulty in NIR-based sorting, as their composite structure can interfere with accurate material identification (Horodytska et al. 2018; Koinig et al. 2022a, 2022b, 2024).

To underscore the significance of enhancing existing sorting technologies, this study was conducted to assess the impact of the sorting quality on the properties of recyclates. Four distinct sorting qualities were examined: one derived from commercial waste, while the remaining three originated from three different sorting facilities from different companies, which sent their output to a plastic recycling facility in Austria. The three grades from the sorting facilities were first characterized based on their composition. Subsequently, all four qualities underwent pre-treatment and mechanical recycling. The resulting four recyclates were then compared against three commercially available recyclates to evaluate their respective properties.

Materials and methods

Materials

Grade 1 was compiled based on the composition of commercial wastes in Upper Austria (Langwieser et al. 2024). The waste consists of 30% large and transparent polyethylene (PE) films, 10% large colored PE films, 30% transparent packaging PE films, and 30% colored packaging PE films.

Samples labeled Grade 2, Grade 3, and Grade 4 were obtained from a plastic recycling facility in Upper Austria, where pre-sorted bales of PE films from different suppliers

are processed. Here, samples were drawn from waste bales originating from Austria, Italy, and Germany, as they were expected to differ most due to different packaging, collection systems, and specification standards. Despite these differences, all three streams were processed under the same specification, defined by “Duales System Deutschland (DSD) GmbH” as DSD 310. This specification requires the sorted film fraction to consist primarily of used, residue-emptied PE plastic foil with an area larger than DIN A4, such as bags, shrink films, closures, and labels, with a minimum purity of 92%.

Sampling was conducted following CEN/TR 13310–2:2006, as the bales were opened, singularized, and homogenized with a pre-shredder and then regularly drawn from the moving conveyor belt. Each sample was collected with a 90 L tub (3–5 kg) covering the whole width of the conveyor belt. Twenty-four samples were taken from bales originating from Austria (Grade 2), seventeen samples originating from Italy (Grade 3), and sixteen samples originating from Germany (Grade 4).

After sampling, Grade 2, Grade 3, and Grade 4 were sorted manually, separating films from rigid items and material types. As the PE low-density (PE-LD) films were the focus of interest, the PE-LD fraction was sorted into colored and transparent films together with their original application (packaging, heavy-duty bag, refuse bag, stretch film). In total, the 25 fractions listed in Table 1 emerged. The material type was analyzed with a near-infrared handheld device (microPHAZIR Analyzer, Thermo Fisher Scientific). A film was considered transparent when translucent and less than 10% of it was printed; its application was derived based on apparent evidence such as print, decoration, or size. After sorting, each category was weighed, and the mean composition calculated.

A comparison of the four distinct waste streams was enabled by the characterization of three commercially available recyclates with different qualities, which were produced by Walter Kunststoffe GmbH (Gunskirchen, Austria). The three grades of film waste are distinguished by their respective sorting, washing, filtering, and coloration processes. The first, designated P-01, is a PE-LD/PE linear low-density (PE-LLD) polymer granulate from post-consumer recycling that has undergone a rigorous sorting, washing, filtering, and light-coloring process ([Online]. Available: <http://www.walter-kunststoffe.com>, content, de, produkte-regenerate (accessed 2025a). The second, designated P-03, is a dark-colored PE-LD/PE-LLD polymer granulate from post-consumer recycling. It is a highly sorted, washed, melt-filtered, and gray-green PE-LD/PE-LLD polymer granulate with a pronounced inherent color ([Online]. Available: <http://www.walter-kunststoffe.com>, content, de, produkte-regenerate (accessed 2025b). The third product (P-05) is a washed, coarse melt-filtered, dark natural-colored PE-LD/PE-LLD

Table 1 Components found in the waste bales of Grade 2, Grade 3 and Grade 4

<i>Pe film</i>	PE film clear/large
	PE film clear/stretch
	PE film clear/packaging
	PE film color/large
	PE film color/stretch
	PE film color/refuse bags
	PE film color/packaging
	PE film color/heavy-duty sack
	PE high-density (PE-HD) film
<i>Polyolefins (PO)</i>	PE-HD rigid
	Polypropylene (PP) film
	PP rigid
<i>Other polymers</i>	Polyvinyl chloride (PVC)
	Polyethylene terephthalate (PET)
	Polystyrene (PS)
<i>Others</i>	Organics
	Multi-material multi-layer packaging
	Multicomponent
	Paper & Cardboard
	Beverage Cartons
	Metal
	Nets, straps, ribbons, woven systems
	Textiles
	Gloves
Fines (< 40 mm)	

polymer granulate from post-consumer recycling ([Online]. Available: <http://www.walter-kunststoffe.com>, content, de, produkte-regenerate (accessed 2025c).

Pre-treatment

In order to facilitate the processing of the sorted films, the material needed to be pre-treated. The initial step in the pre-treatment process involved the shredding of the material. For this purpose, a Retsch SM300 (Retsch GmbH, Haan, Germany) at a speed of 800 rpm with a sieve the size of 20 mm was utilized. Subsequently, to ensure the removal of any excess contaminations and harmful particles such as metals, swim-sink separation was performed using an intermediate bulk container where the top was cut off with a holding capacity of 1000 L. 2 kg per film material was introduced into the room-temperature water, thoroughly stirred, and permitted to settle for a duration of 5 min. The floating materials were then collected, and the process was repeated with the next 2 kg. Further washing was performed using a washing machine Miele PW818 (Miele GmbH, Wals, Austria). In this step, 2 kg batches of shredded and pre-washed film material were washed using 35 L of water with 875 g (2.5 w%) sodium hydroxide (NaOH, purity 99% (Algin,

Neustadt-Glewe, Germany)) for 15 min at 80 °C. To ensure complete removal of residual detergents, the material was again washed with 35 L of water for a duration of 5 min at a temperature of 25 °C. After washing, the material was dried in a Binder FED 56 heating oven (Binder GmbH, Tuttlingen, Germany) at 60 °C for 4 h. To reduce the bulk density and ensure a constant feed into the compounder, the dried material was compressed into pellet form using a PP200C pellet press (EverTec, Dieburg, Germany) equipped with a matrix plate having a die hole diameter of 6 mm.

Processing

The pre-treated material was then processed through a twin-screw extruder ZSE 18MAXX (Leistritz AG, Nuremberg, Germany) at a screw speed of 350 rpm with a throughput varying between 1.0 and 1.5 kg/h and a melt temperature of approximately 210 °C. At the screw tip, the molten material was filtered using a mesh size of 60, which relates to a hole size of approximately 0.25 mm. For the determination of the optical and mechanical properties, the produced granules were processed into films using an OCS ME30 measuring single screw extruder (OCS Optical Control Systems GmbH, Witten, Germany). The screw speed was set at 20 rpm, resulting in a melt temperature of approximately 210 °C. The melt was extruded through a 150 mm × 1 mm sheet extrusion die onto chill rolls set at 30 °C with a take-off speed of 5.6 rpm to create a film thickness of approximately 100 µm. The holding tension was set at 6 N, and the rewinding tension was set at 7 N.

Characterization

Oxidation onset temperature (OOT)

The OOT measurements were performed using a DSC 4000 instrument (Perkin Elmer Inc., Waltham, MA, USA) in accordance with ISO 11357-6 (Plastics—Differential scanning calorimetry (DSC)—Part 6: Determination of oxidation induction time 2018). Per sample approximately 5.0 ± 0.5 mg was weighed and heated from 30 °C to 280 °C at a heating rate of 10 K/min. At least two measurements per investigated material fraction were performed. The samples were heated continuously in an air atmosphere until a characteristic temperature was reached, indicating the onset of an exothermic event and oxidative degradation, as indicated by a baseline shift.

Ash content

The ashing process was carried out in accordance with ISO 3451-1 (Plastics—Determination of ash—Part 1: General methods et al. 2019) standard procedure, employing quartz

fiber crucibles and a Phoenix microwave muffle furnace (CEM Corporation, Matthews, North Carolina, USA). Approximately 3 g of material was placed in each crucible and subjected to direct calcination in the muffle furnace at 750 °C for 15 min. After calcination, the crucibles were weighed and the ash content was calculated using Eq. (1):

$$A\% = \frac{m_1}{m_0} \times 100 \quad (1)$$

where A% is the resulting ash content, m_0 is the initial mass of the test sample, and m_1 is the measured mass of the obtained ash. It is important to note that each of the six samples was tested three times.

Density

The density was measured according to ISO 1183–1 (Plastics—Methods for determining the density of non-cellular plastics—Part 1: Immersion method, liquid pycnometer method and titration method 2019) using a QUINTIX224-1S and a density kit YDK03 (Sartorius AG, Gottingen, Germany). For this purpose, pellets were pressed to discs of 20 mm diameter and 2 mm height. These discs were produced on an Atlas 15 T press (Specac Ltd., Orpington, UK) at approximately 210 °C for 3 min. Per sample, three density measurements in ethanol were performed.

Melt mass flow rate (MFR)

The MFR was measured according to the ISO 1133 (Plastics—Determination of the melt mass flow rate (MFR) and melt volume flow rate (MVR) of thermoplastics 2022) using an Aflow (ZwickRoell GmbH and Co. KG, Ulm, Germany) with a testing weight of 2.16 kg at a temperature of 190 °C. Approximately 3 g of material was loaded into the pre-heated cylinder of the measurement device, where it was compacted and heated for five minutes, and the measurement was started automatically. Six strands from the center mass were extruded, cut, and weighed.

Optical contamination detection (OCD)

OCD was performed using the above described single screw extruder OCS ME30 with an FSA100 modular film analyzer (OCS Optical Control Systems GmbH, Witten, Germany). Contamination measurements were performed with a base grayscale value of 180, with the measurement system triggered upon detection of a 20% deviation (darker). To ensure optimal camera detection, all samples were blended with a virgin PE Borstar FB4230 (Borealis AG, Wien, Austria) at a ratio of 90% virgin to 10% recycled material. For the contamination detection approximately 5 m² of film per sample

was investigated. For the determination of size distribution, the inclusions were clustered into categories 0–299 µm, 300–599 µm, 600–1000 µm, and > 1000 µm. The resulting numerical values for contaminations per m² have been reported as measured.

Transparency

The transparency of the samples was characterized by measuring the total transmittance (including both direct and diffuse fractions) across the visible range of 300–800 nm using a PerkinElmer Lambda 950 UV–VIS–NIR spectrometer (PerkinElmer Inc., Waltham, MA, USA). The recorded transmittance spectrum was averaged to obtain a single value representing the transparency of each sample. This measurement was conducted thrice for each sample.

Tensile properties

Tensile properties were measured in accordance with ISO 527–3 (Plastics—Determination of tensile properties—Part 3: Test conditions for films and sheets 2018) using the zwickiLine Z2.5 testing machine (ZwickRoell GmbH and Co. KG, Ulm, Germany), which was equipped with a load cell with a nominal force of 500 N. Specimens of type 5 were tested with a pre-load of 0.1 MPa and a testing speed of 50 mm/min until failure by fracture occurred. As stated in the standard, at least 5 specimens per material were tested.

Puncture resistance

Puncture properties were determined in accordance with the requirements of EN 14477 (Packaging– Flexible packaging material– Determination of puncture resistance– Test methods et al. 14477 2004) using the zwickiLine Z2.5 testing machine (ZwickRoell GmbH and Co. KG, Ulm, Germany). The films were tested at a test speed of 50 mm/min until failure by breakage occurred. As stated in the standard, at least 10 specimens per material were tested.

Results and discussion

Composition analysis

Figure 1 illustrates the total composition of waste classifications Grade 2, Grade 3, and Grade 4. Notably, Grade 2 and Grade 3 exhibit comparable proportions of PE film, with approximately 87.1% and 84.0%, respectively. In contrast, Grade 4 contains the lowest proportion of PE film, accounting for approximately 59.6%. Analysis of Table 2 reveals that the predominant fraction within Grade 2 is PE film color, comprising approximately 65.2% and PE film

Fig. 1 Composition of the waste categories identified of Grade 2, Grade 3, and Grade 4

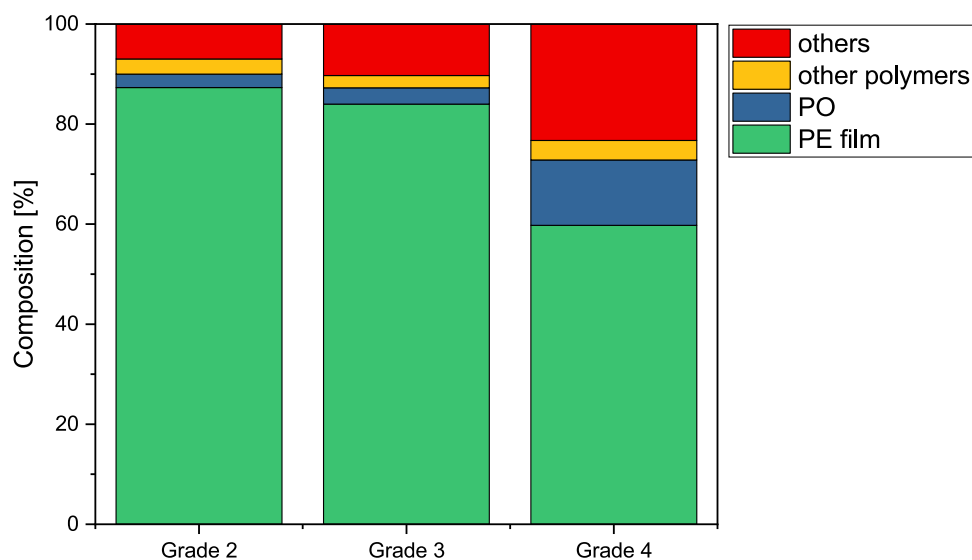


Table 2 Mean values and standard deviations of the composition of the total PE Fraction

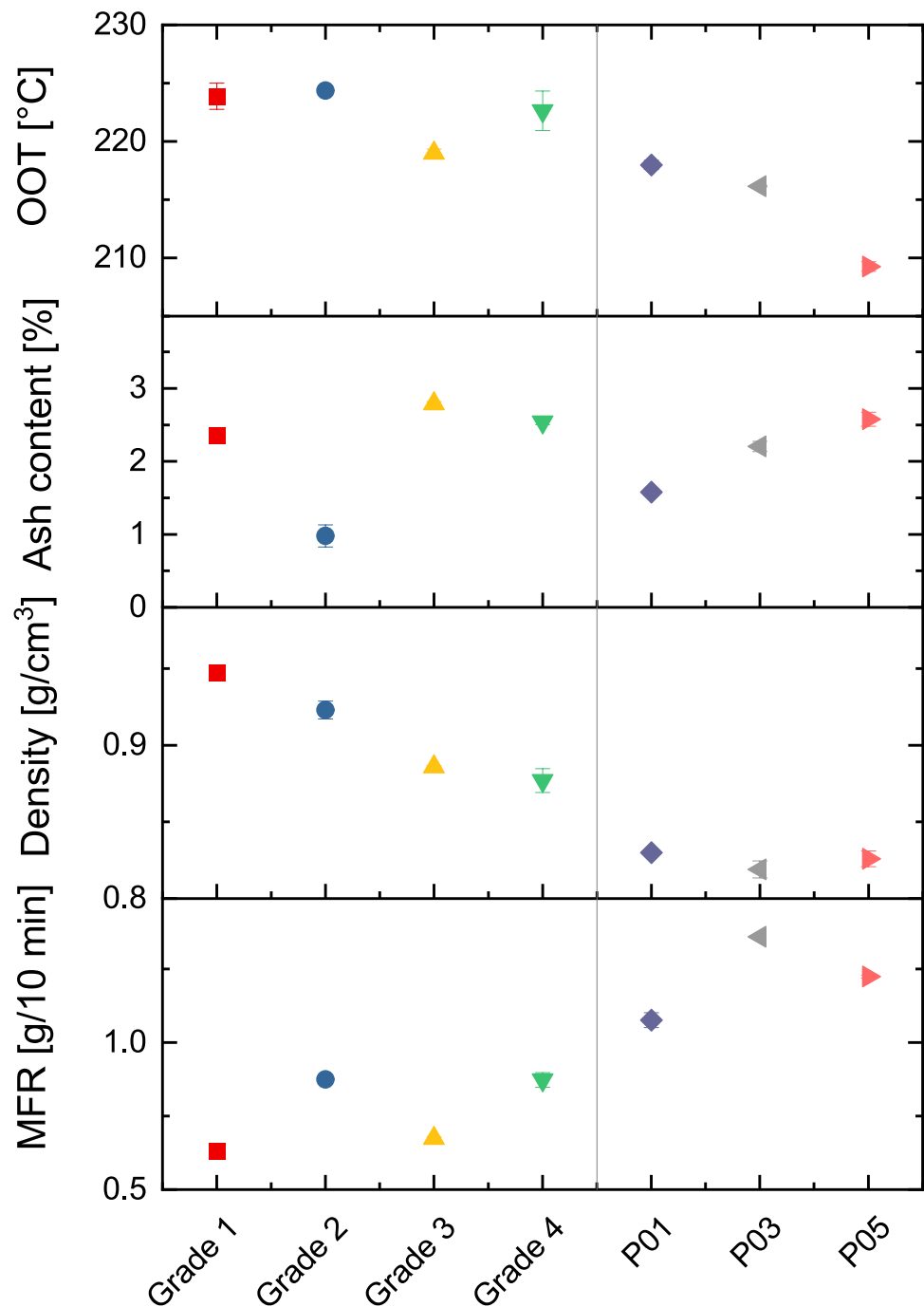
	Grade 2		Grade 3		Grade 4	
	Mean [%]	Standard deviation	Mean [%]	Standard deviation	Mean [%]	Standard deviation
PE film color	65.2	19.9	43.9	10.8	34.9	12.1
PE film clear	21.4	15.9	38.9	11.0	24.3	5.9
PE-HD film	0.7	1.0	1.2	1.0	0.6	0.6
<i>Total PE film</i>	87.3	9.2	84.0	12.6	59.8	16.0
PO	2.7	0.5	3.2	0.9	13.1	2.8
Other polymers	3.0	1.0	2.4	0.7	3.9	1.2
Others	7.0	0.5	10.4	1.4	23.2	2.6
<i>Sum others</i>	12.7	2.0	16.0	3.5	40.2	7.9

clear, comprising approximately 21.4% of the total. The smallest fraction within Grade 2 is PE-HD film, representing only 0.7%. Within Grade 3, the most abundant fraction is PE film color, constituting 43.9% of the total, about 38.9% of PE film clear, and PE-HD film again exhibits the lowest amount with approximately 1.2%. Similarly, Grade 4 exhibits PE film color as the dominant fraction at 34.9%, followed by PE film clear at 24.3%, and PE-HD film at 0.6%. Across all three grades, other materials and packaging (depicted in red in Fig. 1) constitute a notable fraction. Specifically, Grade 2 contains approximately 7%, Grade 3 around 10%, and Grade 4 more than 20% of such contaminations. In contrast, only minor proportions of other polymer types were identified in all three grades. Despite being processed under the DSD 310 specification, none of the three waste streams fully met the required purity of 92%, highlighting inconsistencies in sorting efficiency and input material quality.

Basic properties

As illustrated in Fig. 2, the OOT measurements indicated rather constant values for Grade 1 to Grade 4, while lower values were observed for samples P01, P03, and P05. Notably, P05 exhibited the lowest OOT among all samples. These variations may be attributed to the presence of organic contaminations within the recyclates, since their origin is post-consumer waste, which often times still has residues from food produce or others on them, which contain oxygen and promote premature oxidation during heating processes, such as extrusion, thereby reducing the oxidation temperature (Langwieser and Fischer 2024). The oxidation behavior furthermore is influenced by the origin of the waste stream and the additives used in the material. Additives are selected by the polymer producer based on the specific field of application of the product made from the polymer. Antioxidants are used to inhibit premature oxidation processes. Over the

Fig. 2 Basic properties: OOT, ash content, density and MFR of the four different sorting grade-recyclates and three commercial recyclates



product's lifetime, a certain amount of the antioxidants is consumed, and small quantities of residual stabilizers may still remain at the end of life of a product (Kirschweg et al. 2017; Langwieser et al. 2022). This consumption contributes to a reduction in oxidation temperature. The measured OOT values for the differently sorted samples fall within the typical processing temperature range for PE, which is 190 to 250 °C (Baur et al. 2019). Based on the measured OOT values of this study, the material is deemed suitable for low-temperature processing methods, such as extrusion.

As depicted in Fig. 2, no discernible trend was identified among Grade 1 and Grade 4 concerning the ash content in the recyclates. With regard to the commercially available recyclates, P01 exhibited the lowest values, followed by an increase for sample P03, and a further increase for P05. With the exception of Grade 2, all materials exhibited a correlation with the oxidation onset temperature (OOT), wherein a lower OOT corresponded to a higher ash content. This trend is evident when comparing Grade 1, Grade 2, and Grade 3, as well as P01, P03, and P05. Although the measurement

of ash content is not the most precise method for analyzing inorganic content, it offers the advantage of analyzing a relatively large sample size. Consequently, it is a more representative technique for assessing inhomogeneous material streams compared to other methods.

As the data in Fig. 2 illustrate, the density of the materials decreased from Grade 1 to Grade 4. In addition, sample P01 had a lower density than Grade 4, and P03 had an even lower density than P01. P05 had a lower density than P03, exhibiting the lowest value of all characterized samples. Notably, five out of seven samples exhibited densities below 0.9 g/cm^3 , which is lower than expected for typical PE film materials. These variations can be linked to polymer structural properties, including crystallinity and molecular weight. The polymer structure in recycled polymers is strongly influenced by degradation mechanisms that occur during their lifetime and reprocessing (Langwieser et al. 2022; Petukhova et al. 2023; Pinheiro et al. 2004; Mendes et al. 2011). For example, in PE, chain branching inhibits the formation of crystals and therefore reduces the density overall. Crystalline regions are critical for the density of a polymer, as they allow for tightly packed polymer chains, resulting in an increase in density (Baur et al. 2013; Eyerer et al. 2005). However, no direct measurements of crystallinity (e.g., via DSC or XRD) were conducted in this study, and the level of crystallinity required to achieve densities below 0.9 g/cm^3 remains uncertain. The presence of impurities or contaminations in recycled materials can hinder the nucleation and growth of crystalline regions, thereby influencing the density. The influence of additives, particularly fillers incorporated during the polymer's initial application, is also significant. Depending on their type, concentration, and dispersion, fillers can alter the density of polymers just like contaminations, either enhancing or diminishing the overall density of the material (Gall et al. 2021). For example, contaminations such as polypropylene (PP) or polyolefin plastomers/elastomers, which are characterized by low densities and low crystallinity, could contribute to the observed density values. However, while the overall contamination levels were measured, the specific types and amounts of these contaminations were not quantified in this study. Further analysis (e.g., FTIR or TGA) would be required to confirm their presence and assess their impact. Additionally, the density values for the commercial recyclates (P01, P03, and P05) were not consistent with their respective data sheet values. This discrepancy may be due to differences in the specimen preparation procedure or the specific conditions under which the density measurements were conducted. For example, the density measurement method used in this study may yield slightly different results compared to the methods used by manufacturers to determine data sheet values. Variations in sample preparation, such as residual moisture, trapped air, or incomplete homogenization, could also influence the

measured density values. Especially contaminations, which lead to gasing of inside the material, may lead to a decrease in density, which is often inhibited in industrial processes using anti-foaming additives.

As shown in Fig. 2, the MFR values of Grade 1 and Grade 3 exhibited comparable values, approximately 0.6 g/10 min , while Grade 2 and Grade 4 exhibited similar MFR values around 0.9 g/10 min . In contrast, an increase in MFR was observed across the commercially available recyclate samples from P01 to P05, which exhibited values higher than Grade 1 to Grade 4. The MFR is used to quantify the flowability of molten polymer materials and is strongly dependent on the polymer structure. Polymers with higher molar mass exhibit longer and more entangled chains, which restrict chain mobility and reduce the flowability of the molten material, thereby lowering the MFR (Cestari et al. 2021). Different polymer processing methods require specific MFR ranges, such as lower MFR for extrusion processes and higher MFR for injection molding (Morris 2017; Asaclean et al. 2024). In the context of recycled materials, waste streams frequently consist of polymers with varying MFRs, resulting in recyclates with heterogeneous and variable MFR values. This variability reflects the mixed nature of the feedstock and the influence of prior processing conditions (Akhras and Fischer 2024). Concerning the parameters measured for this study, a correlation between density and MFR is evident; polymers with higher densities tend to exhibit lower MFR values.

Optical properties (OCD, transparency)

As depicted in Fig. 3a, an overall increase in contamination levels is observed from Grade 1 to Grade 4, with a notable rise in inclusions for the commercially available recyclates (P01 to P05). Especially Grade 1 and Grade 2 exhibit remarkably low contamination levels, with 250 inclusions / m^2 and 340 inclusions / m^2 , respectively. The remaining samples exhibit varying degrees of contamination, with Grade 3 containing 940 inclusions / m^2 and Grade 4 containing significantly higher contaminations at 3,510 inclusions / m^2 . Among the samples, P01, P03, and P05 demonstrate even greater contamination levels. The observed differences in contamination levels can be partially attributed to the melt filtration sizes and machine sizes used during processing. Grades 1–4 were filtered with a $250 \mu\text{m}$ filter size in a lab-scale setup, while the commercially available recyclates (P01 to P05) were processed with smaller filter sizes (below $200 \mu\text{m}$, as specified in their respective data sheets) in industrial scale setups. In the lab-scale process, the filter size was chosen as small as possible to ensure a stable process while minimizing the need for frequent filter changes, but still having a larger filter size as the industrial process. In contrast, industrial scale processes are subject

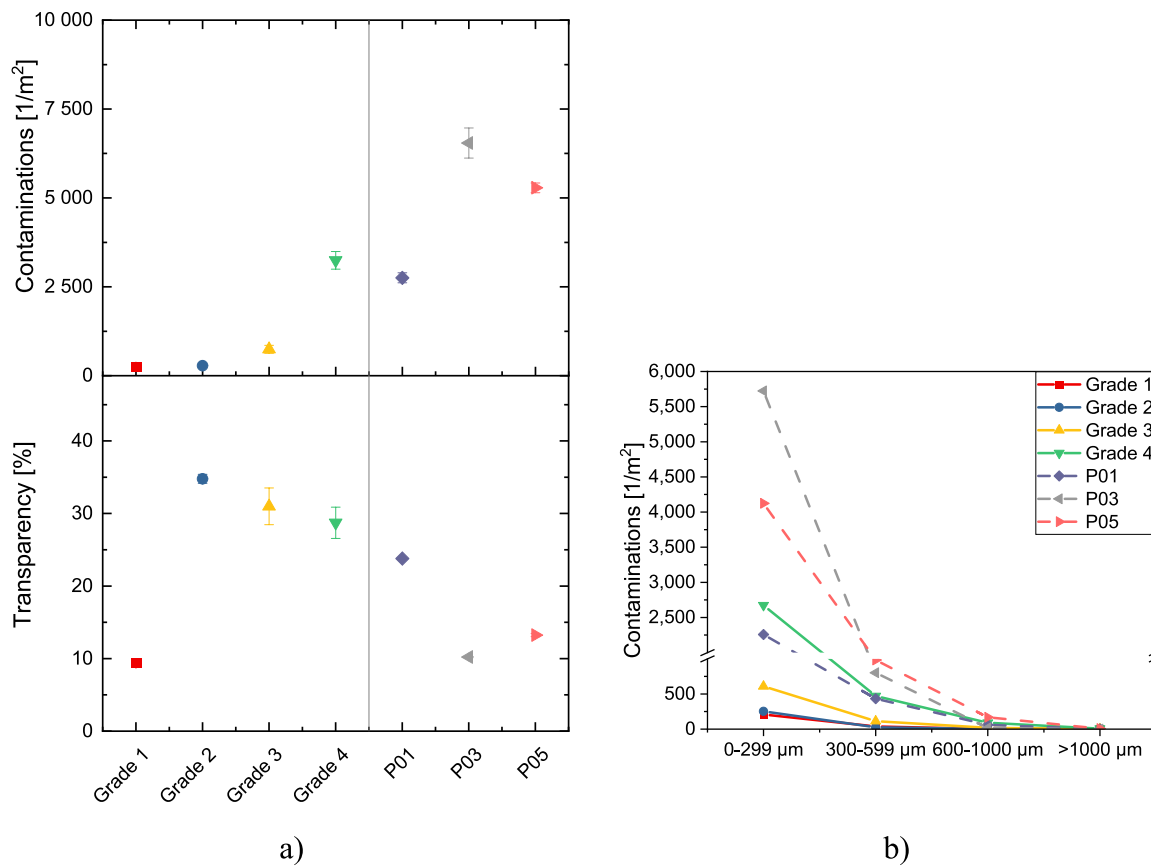


Fig. 3 Optical properties: a) total amount of contaminations per m^2 and transparency values of the four sorting grade-recyclates and the commercial recyclates, and b) size distribution of the contaminations measured during the OCD measurement

to higher pressures in front of the filter, which can lead to the passage of small or deformed contaminations through the filter and can further lead to the breaking apart of contaminants and passing through the filters (Langwieser and Fischer 2024). This may explain the higher contamination levels observed in P01, P03, and P05, despite the use of smaller filter sizes.

Figure 3b illustrates the contamination size distribution. Across all samples, the majority of inclusions fall within the size range of 0–299 μm , with P03 exhibiting the highest quantity of small inclusions in this size class. For Grade 1 and Grade 2, higher size classes exhibit negligible inclusion counts, indicating the high purity of these materials. For the size class 300–599 μm , Grade 3, Grade 4, and P01 exhibit less than 500 inclusions/ m^2 , whereas P03 and P05 show significantly higher levels, ranging between 800 and 1,000 inclusions/ m^2 . In the 600–1,000 μm size class, all samples exhibit relatively low inclusion counts, remaining below 200 inclusions/ m^2 . Noticeably, no inclusions larger than 1,000 μm were detected in any of the analyzed materials. It should be noted that all the materials, as discussed in the Materials and Methods section, were diluted using the same amount of virgin material to make the detection of

contaminations even possible. The aim of this analysis was to present tendencies rather than absolute numbers.

Furthermore, a correlation was observed between the measured contamination quantities and the measured OOT values depicted in Fig. 2. Higher contamination concentrations are associated with earlier oxidation within the material, aligning with the ash content results observed for the commercially available recyclates. This is further reflected in the density measurements, as contaminations inhibit the formation of crystalline regions within the polymer matrix, leading to lower density values.

As depicted in Fig. 3a, the transparency measurements reveal distinct trends across the analyzed materials, with the exception of Grade 1, which exhibits a notably lower transparency level compared to all other grades. Among Grade 2, Grade 3, and Grade 4, a steady decrease in transparency is observed. The commercially available recyclates (P01, P03, and P05) exhibit even lower transparency levels than the other samples, with a further progressive decline.

The transparency of polymeric materials is inherently dependent on the composition of the input waste stream, which is strongly influenced by sorting quality and the criteria used during the sorting process. Sorting based on color

plays a critical role, as mixtures containing dark-colored or opaque materials tend to reduce transparency significantly.

Additionally, the presence of particles or inclusions within the recyclate adversely affects transparency by scattering light and contributing to a reduction in optical clarity. Furthermore, the presence of particles can degrade the perceived color quality of the material, thereby exacerbating the loss of transparency. This is in agreement with the composition analysis of Grade 2, Grade 3, and Grade 4 above; more contaminations lead to lower transparencies.

Mechanical properties (tensile test, puncture test)

As depicted in Fig. 4a, a steady decrease in strain values, measured in both the machine direction (MD) and transverse direction (TD), is observed across Grade 1 to Grade 4 as well as P01 to P05. Notably, Grade 1 and Grade 2 exhibit higher strain values in TD compared to MD, while all other samples depict the opposite behavior, with MD strain exceeding TD strain. Similarly, the stress values exhibit a consistent decrease in MD and TD across Grade 1 to Grade 4 and P01 to P05. In this case, MD stress values are consistently higher than those measured in TD for all samples. The observed differences between MD and TD tensile properties can be attributed to the processing conditions of the polymer film. In the MD, polymer chains are pre-stretched and oriented during the manufacturing process, leading to a higher degree of alignment. In contrast, during testing, no clamping system or external stabilization was employed to restrain the film in the transverse direction, allowing the polymer chains to contract more freely (Morris 2017). This lack of pre-orientation in the TD results in distinct mechanical behaviors, such as strain hardening in the MD and cold drawing in the TD, which influence the material's response to applied stresses (Barlow and Morgan 2013). The decreasing trend in tensile properties correlates with the average size distribution of inclusions in the 300–599 μm range. These inclusions, which are larger than the thickness of the film, act as distortions within the film matrix. Such inclusions disrupt the continuity of the polymer structure, leading to stress concentration points that reduce both the strength and elongation capacity of the material (Traxler et al. 2023).

As shown in Fig. 4b, the puncture property displacement at maximum force (L_M) shows relatively consistent behavior across Grade 1 to Grade 4, with only minor variations observed. In contrast, the commercially available recyclates (P01 to P05) exhibit an increasing trend in L_M , particularly for samples P03 and P05. These two recyclates demonstrate the largest L_M values and exhibit wide error ranges, indicating substantial variability in their mechanical behavior. Similarly, the puncture property maximum force (F_M) values for Grade 1 to Grade 4 are relatively uniform, with minimal fluctuations. However, for the recyclates (P01

to P05), a noticeable increase in F_M is observed for samples P03 and P05. These samples also show greater variability in F_M compared to the other grades, reflecting the heterogeneity of these materials. The observed trends in L_M and F_M correlate with the size distribution data obtained from the OCD measurements. The recyclates (P01 to P05) contain a greater number of larger-sized inclusions compared to the other samples. Larger inclusions or irregularities in the polymer matrix can act as stress concentration points, leading to localized disruptions during mechanical testing (Traxler et al. 2023). This may explain the higher L_M and F_M values observed for P03 and P05, as well as the greater variability in their standard deviations.

Conclusion

This study evaluated the impact of sorting quality on the properties of flexible film recyclates by analyzing four sorting grades (Grade 1 from commercial waste and Grades 2–4 from a post-consumer plastics recycling facility) and comparing them to three commercially available recyclates (P01, P03, and P05).

The results highlight that sorting quality plays a critical role in determining recyclate composition, contamination levels, and overall performance. Grades 2 and 3, with high PE film proportions (87.1% and 84.0%, respectively), exhibited better properties compared to Grade 4, which had significantly lower PE content (59.6%) and higher contamination (23.2%). Poorer sorting quality was directly linked to increased contamination and reduced recyclate performance.

However, the differences between Grades 1 and 4 and P01, P03, and P05 cannot be attributed to sorting alone. Washing and melt filtration also play significant roles. For example, the lower oxidation onset temperature (OOT) observed in commercial recyclates, particularly P05, is likely due to organic contaminants that were not effectively removed during industrial washing. Similarly, the higher contamination levels in P01, P03, and P05, despite the use of smaller filter sizes, may be explained by the higher pressures in industrial scale melt filtration, which can allow small or deformed contaminants to pass through or to break apart and increase the numbers of contaminations.

In terms of applicability, the diverse recyclate qualities suggest different potential uses. Grades 1 and 2, with their high PE content, low contamination, and better mechanical properties, are suitable for film-to-film recycling and could replace virgin materials in certain film applications. In contrast, Grade 4 and P05, with higher contamination and poorer mechanical properties, may be more suitable for non-film applications, such as pipe extrusion or injection molding. This aligns with the datasheet of P05, which specifies its suitability for these applications but not for film extrusion.

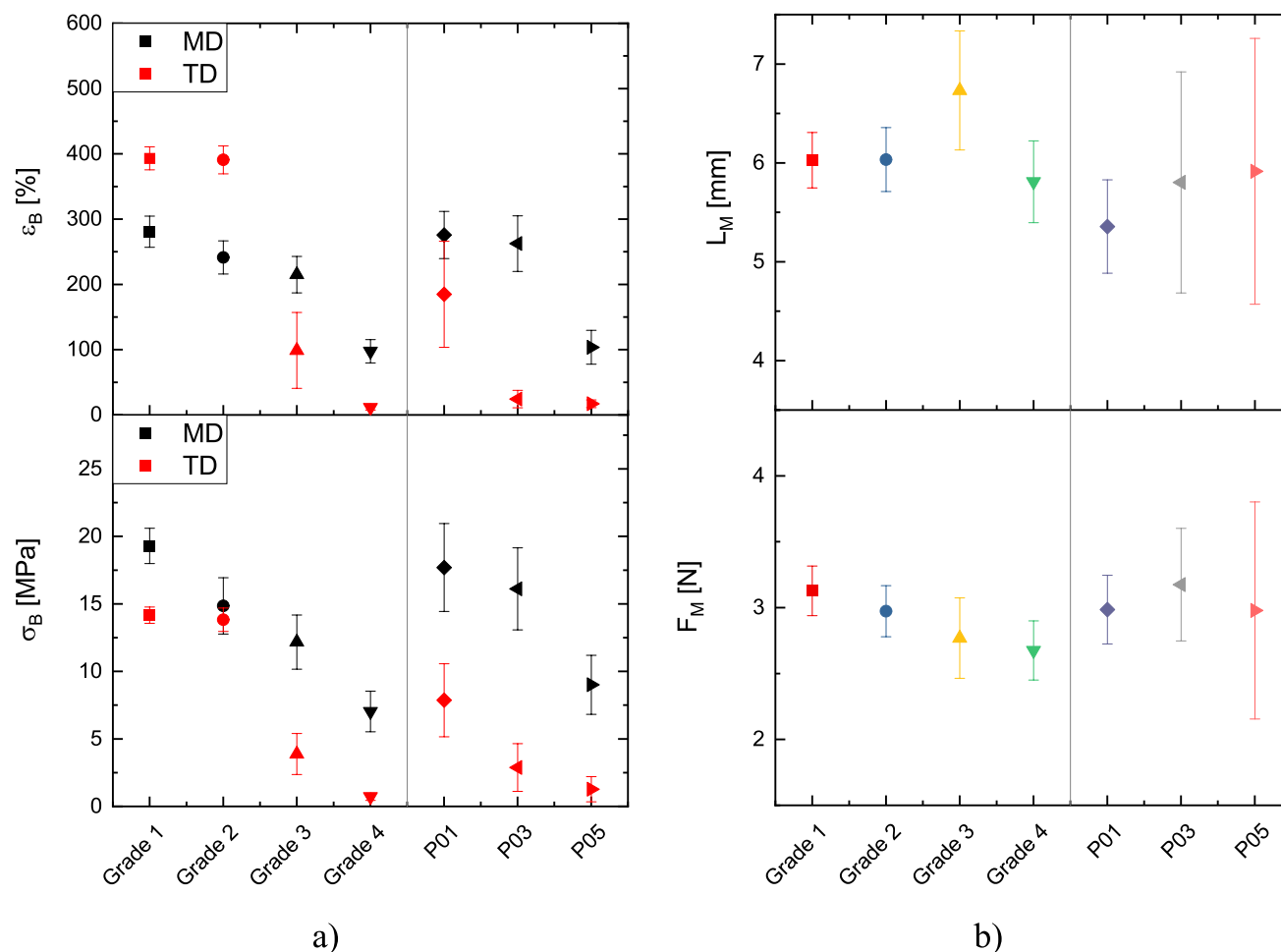


Fig. 4 Mechanical properties of the four sorting grade-recyclates and the commercial recyclates: a) tensile properties strain at break ϵ_B and stress at break σ_B , and b) puncture properties displacement at maximum force L_M and maximum force F_M .

These findings emphasize the importance of matching recyclate quality to specific application requirements.

This study demonstrates that improved sorting, combined with optimized washing and melt filtration processes, leads to higher-quality recyclates. Future research should focus on quantifying the specific contributions of each processing step (sorting, washing, and melt filtration) to recyclate quality. Additionally, efforts should be made to align recyclate properties with market specifications and to explore their potential to replace virgin materials in various applications. Advancing sorting technologies, optimizing waste collection systems, and fostering market demand for high-quality recyclates are essential to closing the plastic waste loop and supporting the EU's transition to a circular economy.

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Data availability No datasets were generated or analyzed during the current study.

Declarations

Conflict of interests The authors declare no competing interests.

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