

A wide-angle photograph of the TU Wien main building, a large white neoclassical structure with a green roof and many windows, set against a clear blue sky and surrounded by trees and city buildings in the background.

Herausforderungen des mechanischen Recyclings: Warum mechanisches Polymer-Recycling an Grenzen stößt

Vasiliki-Maria Archodoulaki TU WIEN

Motivation for circular economy



Plastics Production



10% is recycled worldwide and
24% in the EU (Packaging 42%)



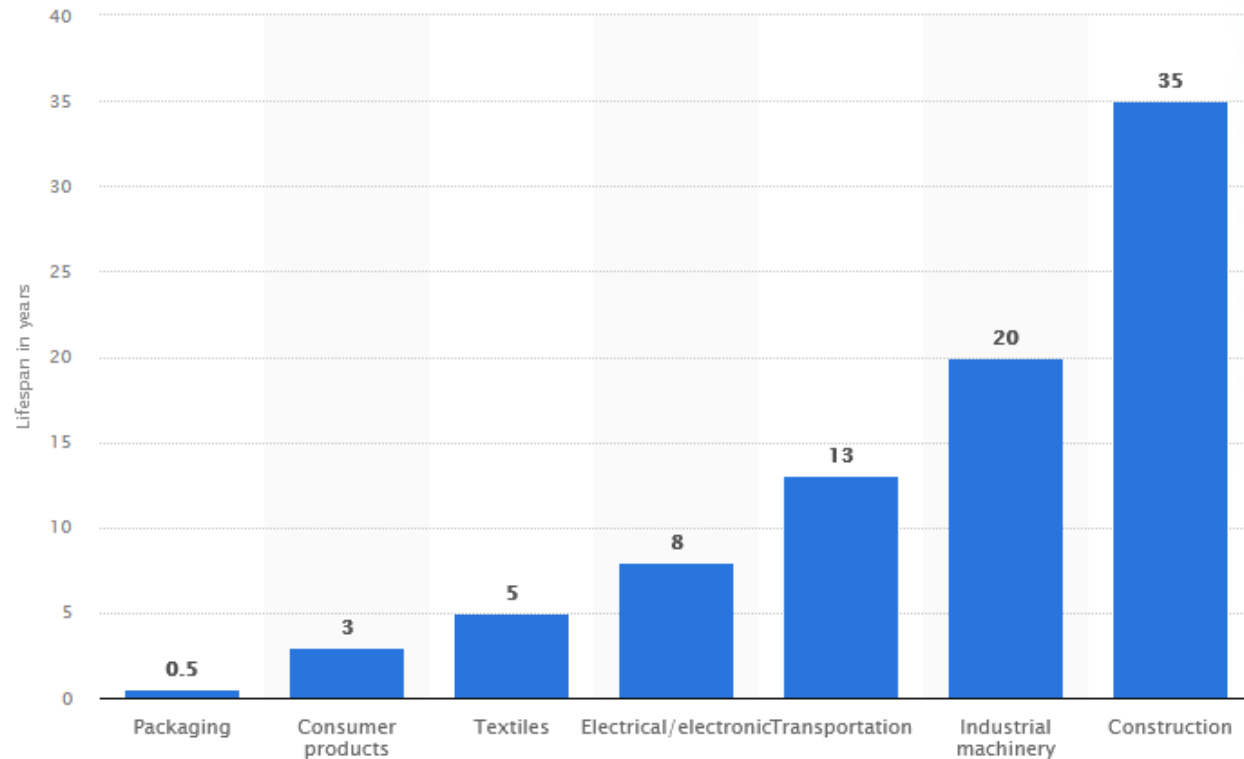
The focus is on packaging



Packaging (31%) (EU 40%)
Construction (16%) (EU 20%)
Vehicles (14%)
Consumer goods (11%)



AVERAGE LIFESPAN OF SELECTED PLASTIC PRODUCTS, BY TYPE , WORLDWIDE, 2024, SOURCE STATISTA 2026



Source Statista

<https://www.undp.org/chemicals-waste/our-work-areas/plastic-pollution>

https://plasticseurope.org/wp-content/uploads/2026/05/Circular-Economy-Report-2026-full-report.pdf?utm_campaign=406326506-Circular%20Economy%20Report%202026&utm_source=dedicated_page&utm_medium=dedicated_page

Global Plastic Flow

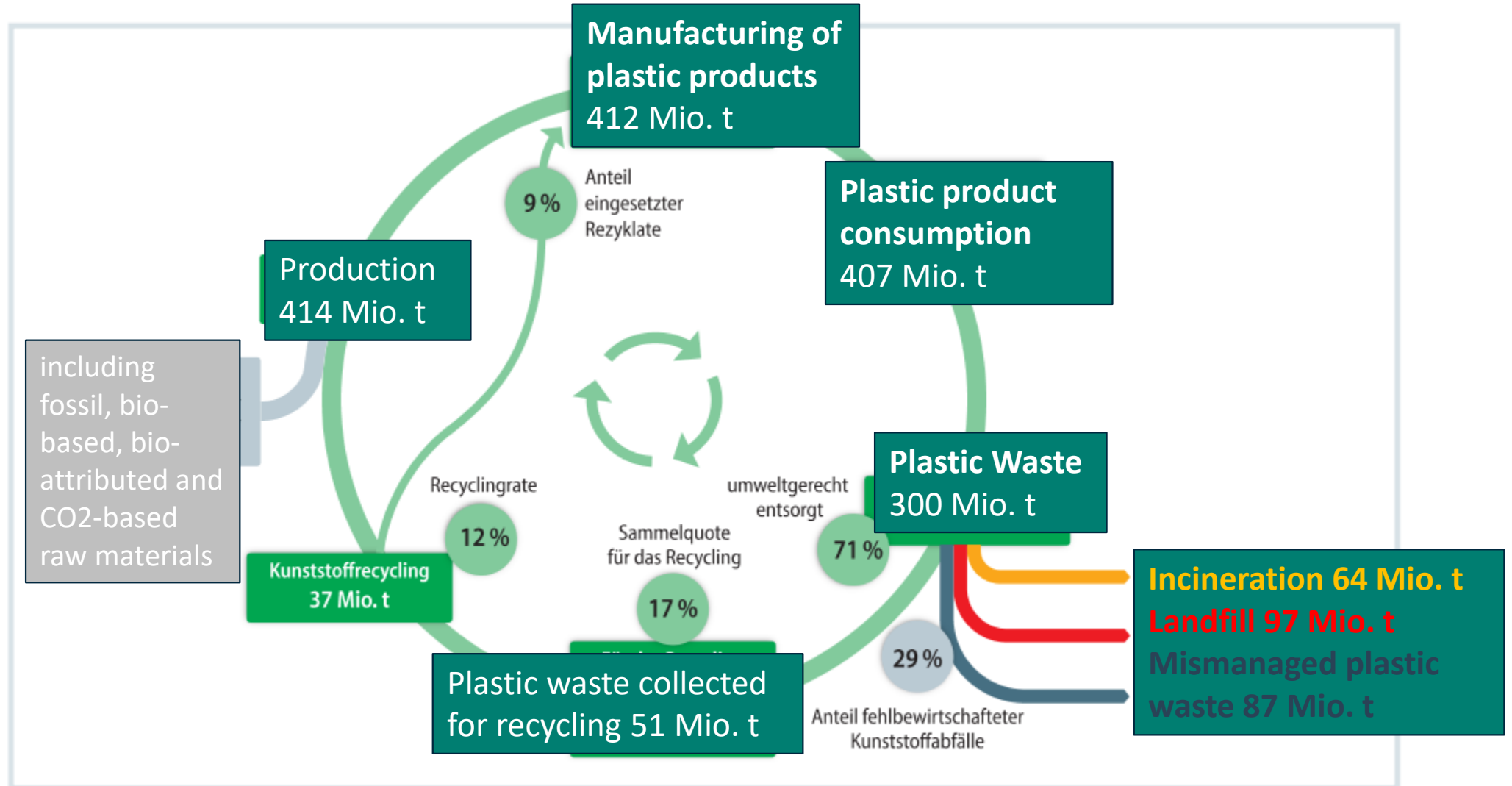
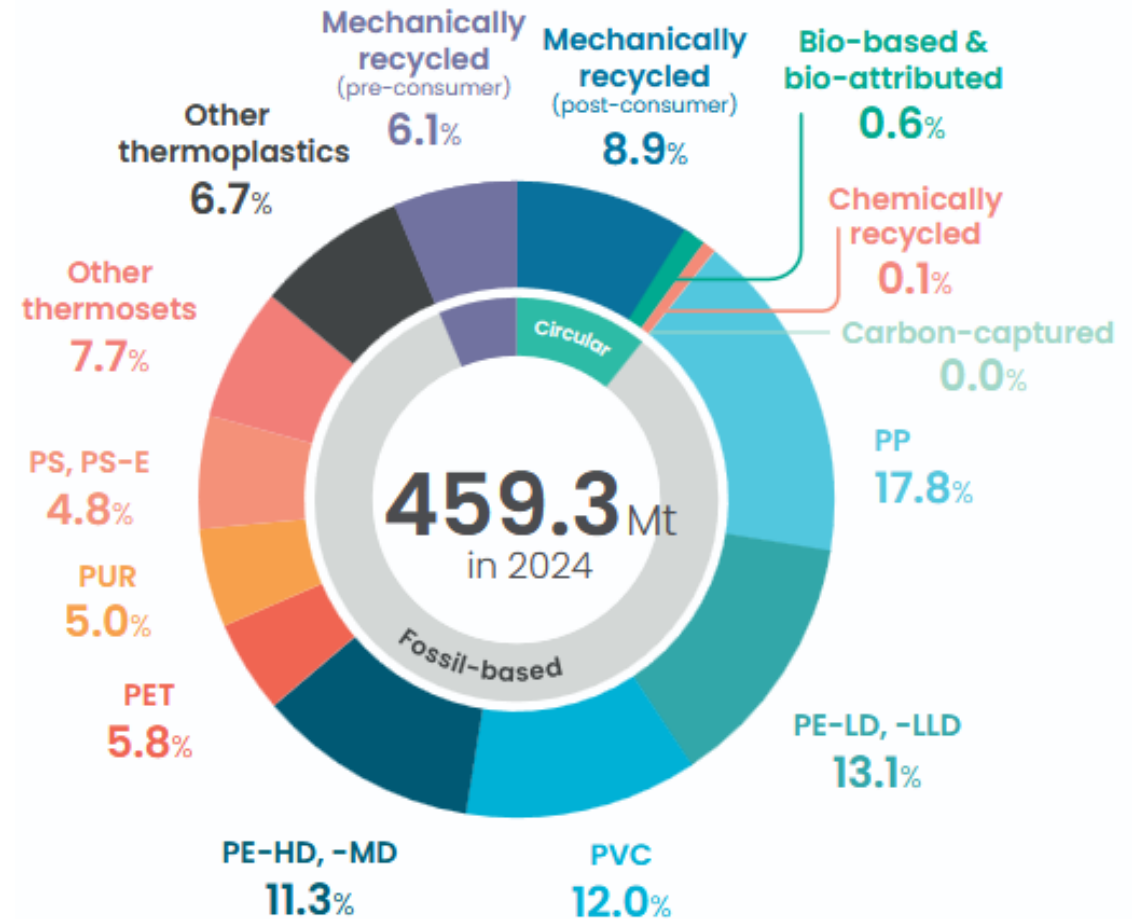


Bild 1. Der globale Kunststoffkreislauf mit Daten aus dem Jahr 2023. Quelle: Conversio Market & Strategy, © Grafik: Hanser

Recycling

- **Global Production:** 414M t (374M t fossil-based).
- **Annual Waste:** 300M t post-consumer (+20% since 2018).
- **Environmentally Sound (71% / 212M t):** Landfill (33%), energy recovery (21%), recycling (17%).
- **Mismanaged (29% / 87M t):** Littered or openly burned.
- **The 12% Gap Sorting Loss:** 51M t collected → only 37M t actually recycled.
- **Stagnation:** Recycled content in global production stuck at 9%.
- plastic recycling rates have to be increased across the EU by 2040. *PPWR: Non-PET bottles: 65% Contact-sensitive packaging: 50% (excluding single-use beverage bottles)*

Global plastics production by polymer

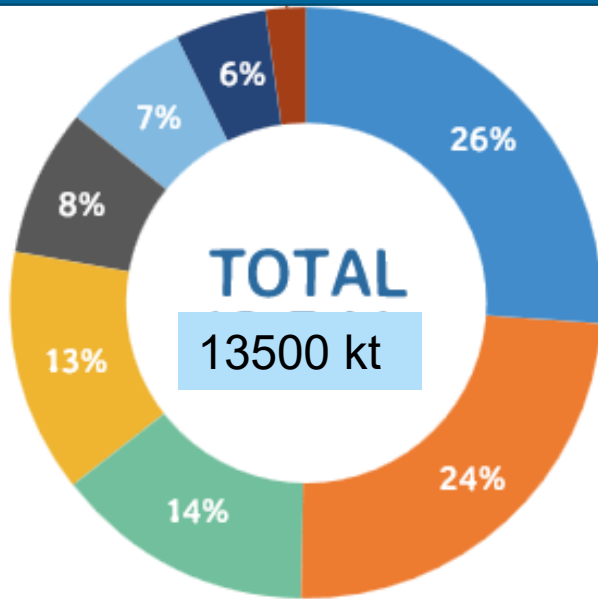


https://plasticseurope.org/wp-content/uploads/2026/05/Circular-Economy-Report-2026-Full-Report.pdf?utm_campaign=406326506-Circular%20Economy%20Report%202026&utm_source=Dedicated_Page&utm_medium=Dedicated_Page

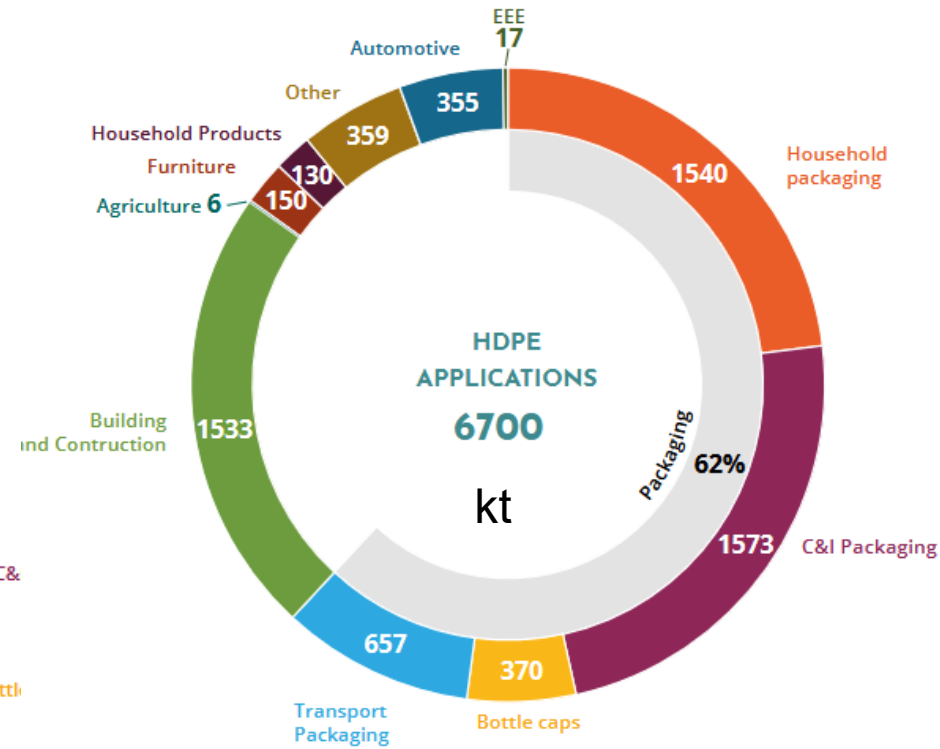
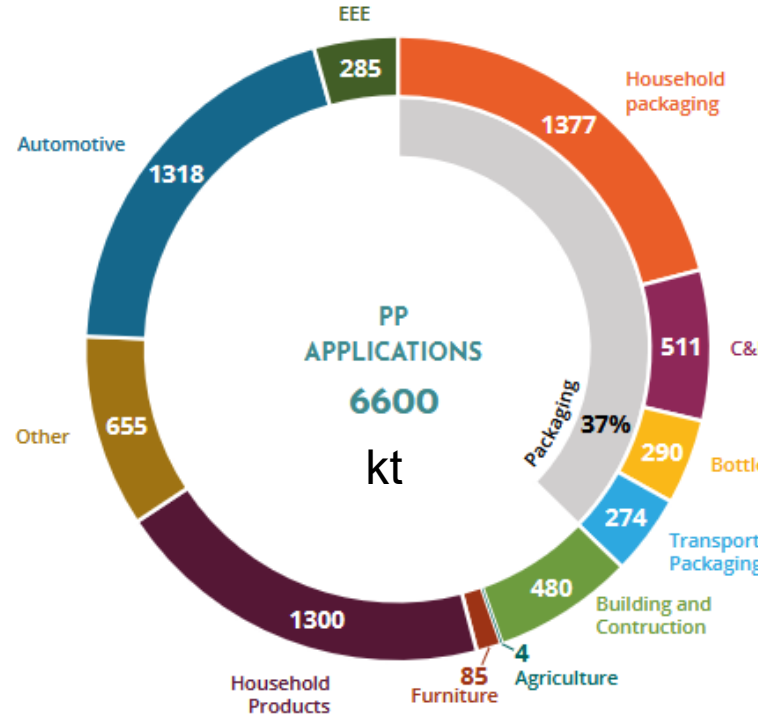
WO STEHT DIE WELT BEIM KUNSTSTOFFRECYCLING KU 12 2025

Applications and Recycling

2024 recycling capacities:
PET 3300 kt, Rigid PP 1800 kt
and PE-HD 1750 kt



PO Films PET PP HDPE
PVC Mixed plastics ELV-WEEE plastics PS/EPS



Use of PE-HD and PP in rigid packaging

2022: 5000 kt of PET in packaging (bottles, sheet (trays), and flexibles) placed on the **European market**. Of this, 3000 kt were collected, bringing the collection rate to 60%. Almost 2700 kt of collected PET waste was sorted for recycling. The sorted for recycling rate in total was 54%. The sorted for recycling rate for beverage bottles was 75%.



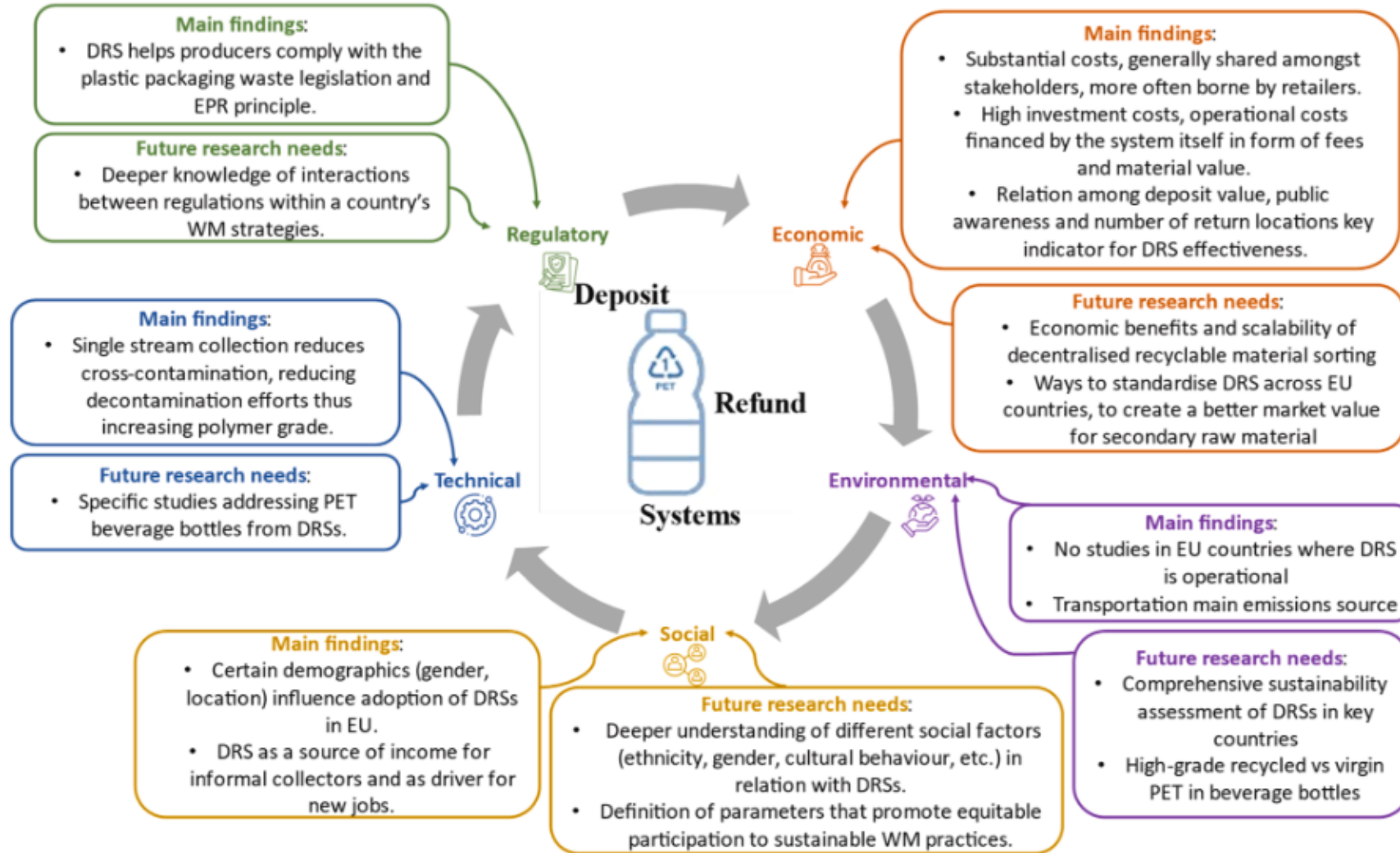
Ambitious goals with the PPWR 2025/40

	By 2025 (%)	By 2030 (%)
All packaging	65	70
Plastic	50	55
Wood	25	30
Ferrous metals	70	80
Aluminium	50	60
Glass	70	75
Paper and cardboard	75	85

https://eur-lex.europa.eu/legal-content/DE/ALL/?uri=oj:L_202500040

The potential of Deposit Refund Systems

The Role of EU Legislation



- **Positive Aspects**
- **High return rates**
- **Reduced littering**
- **High purity.**
- **Public support**

Negative Aspects

- **Rebound effect:** Displaces reusable (refillable) systems.
- **High infrastructure costs**
- **Small business burden**
- **No waste reduction**

C PICUNO, S GERASSIMIDOU, W YOU, O MARTIN, E IACOVIDOU, THE POTENTIAL OF DEPOSIT REFUND SYSTEMS IN CLOSING THE PLASTIC BEVERAGE BOTTLE LOOP: A REVIEW, RESOURCES, CONSERVATION AND RECYCLING, VOLUME 212, 2025, 107962, [HTTPS://DOI.ORG/10.1016/J.RESCONREC.2024.107962](https://doi.org/10.1016/j.resconrec.2024.107962).

The Role of EU Legislation

- The Waste Shipment Regulation (EU) 2024/1157
- EU-wide end-of-waste criteria for plastic waste: European Commission initiative
- The European Commission is proposing new criteria to determine the point when plastic waste is no longer considered as waste when it is used in the manufacture of new goods. At this point it is no longer covered by European Union (EU) plastic waste legislation, and instead is covered by the EU legislation relevant to the new manufactured goods and associated processes

Date	Regulation	Key Enforcement Milestone	Business Impact
May 21, 2026	WSR (EU 2024/1157)	Mandatory Digital Tracking (DIWASS)	Paper-based transit notifications are banned; all cross-border waste shipments within the EU must be logged digitally.
Mid / Late 2026	EoW Plastic Initiative	Official Legal Adoption	The European Commission formally publishes the harmonized technical criteria, defining the legal boundary between waste and product.
November 21, 2026	WSR (EU 2024/1157)	Global Plastic Export Ban	Total ban on plastic waste exports to non-OECD nations; strict independent audits become mandatory for approved OECD exports.
Late 2027	EoW Plastic Initiative	Full Practice Enforcement	Transition period ends. Recyclers must implement certified Quality Management Systems (QMS) to issue official Declarations of Conformity.

Shifting the Recycling Value Chain: From Local Waste to Free Market Commodity

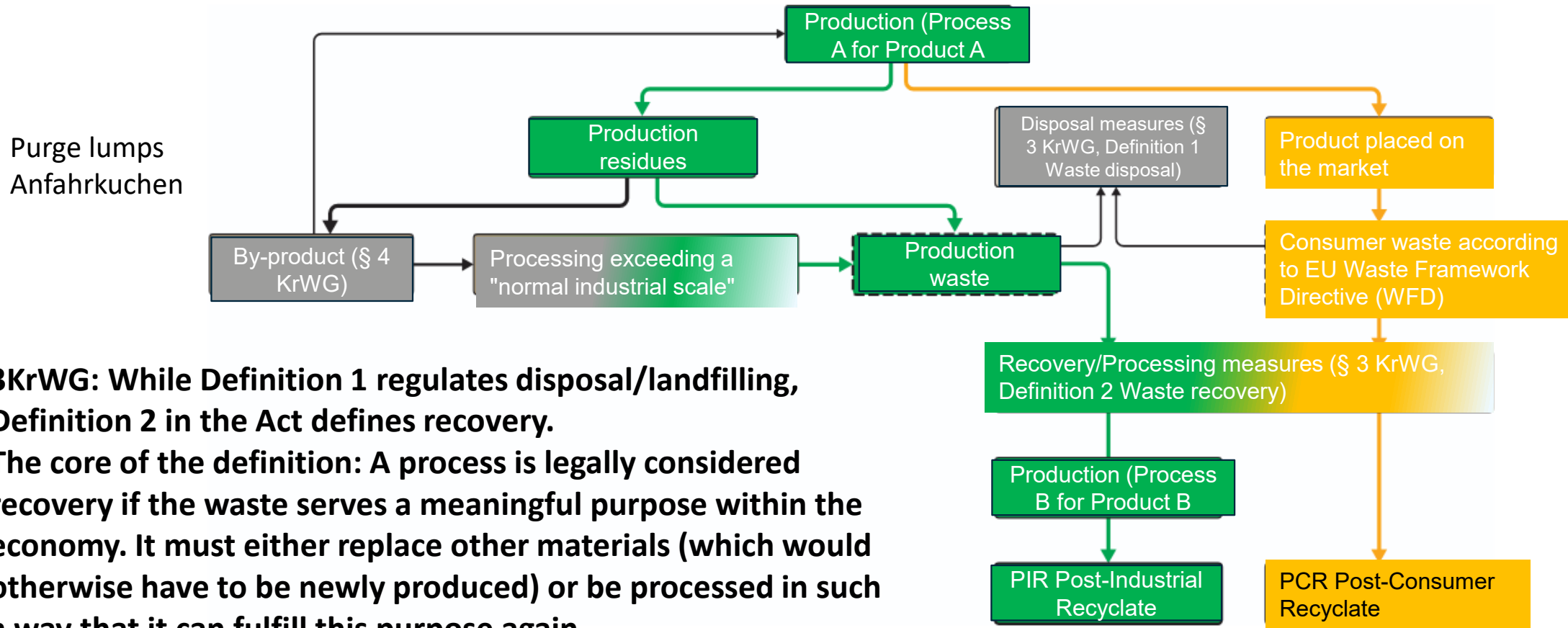
How WSR and End-of-Waste Criteria Force Local Processing to Enable Seamless EU Logistics

- **Enforced Local Pre-Processing:** Because raw and sorted plastic waste faces strict export bans and heavy intra-EU bureaucracy under the WSR, the initial recycling steps—washing, shredding, and compounding—must now take place locally near the source of generation.
- **The "End-of-Waste" Escape Hatch:** The new harmonized EoW criteria act as the legal mechanism to lift the restrictive "waste" label. Once local recyclers transform the material into compliant regranulates, it officially transitions into a standard product.
- **Frictionless Intra-EU Logistics:** Upon achieving product status, the regranulate is completely exempt from complex waste shipment notifications, allowing it to be transported as conveniently and freely as virgin plastic across all member states.
- **The Political Objective:** The EU is cutting off the export of low-quality waste to keep valuable secondary resources, green investments, and industrial processing capacity inside the European circular economy.
- *Essentially, the EU is using a 'carrot and stick' approach to reshape the industry. The **stick** is the Waste Shipment Regulation (WSR), which cuts off cheap exports and imposes heavy bureaucracy on raw waste transport. The **carrot** is the End-of-Waste (EoW) criteria, which rewards high-quality local recycling with completely friction-free logistics across the EU.*

The New EU End-of-Life Vehicles Regulation (ELVR)

- Replaces the old 2000 directive → Now applies **directly and uniformly** across all EU member states (no national transposition needed).
- **Recycled Content Mandates (Circular Economy):**
 - **Plastics:** Minimum **15% recycled content** by approx. 2032 (rising to 25% by 2036).
 - **Closed-Loop:** 20% of that recycled plastic must originate directly from end-of-life vehicles.
- **Design for Circularity:**
 - Vehicles must be engineered for **easier dismantling and component removal**.
 - Mandatory digital **Circular Vehicle Passport** (by 2032) for full material transparency.
- **Extended Producer Responsibility (EPR):** Automakers must cover the costs for collection and complete waste treatment of end-of-life vehicles.
- **Crackdown on Illegal Exports:**
 - Strict, EU-wide criteria to clearly distinguish between a "used car" and "waste".
 - Export ban on non-roadworthy scrap cars starting in 2031.
- **Expanded Scope:** Gradual expansion to include **trucks, buses, and motorcycles** (by 2031).

Classification of material as a by-product or waste



3KrWG: While Definition 1 regulates disposal/landfilling, Definition 2 in the Act defines recovery.
The core of the definition: A process is legally considered recovery if the waste serves a meaningful purpose within the economy. It must either replace other materials (which would otherwise have to be newly produced) or be processed in such a way that it can fulfill this purpose again.

UHRSPRÜNGLICHE GRAFIK AUS: REZYKLAT, DEFINITIONEN, REGELUNGEN UND FALLBEISPIELE KU 5/2026

Closed Loop?

Steel Cans are shredded. Coatings or tin layers are removed. The steel scrap goes to steelworks, where it is melted down and cast into new steel.

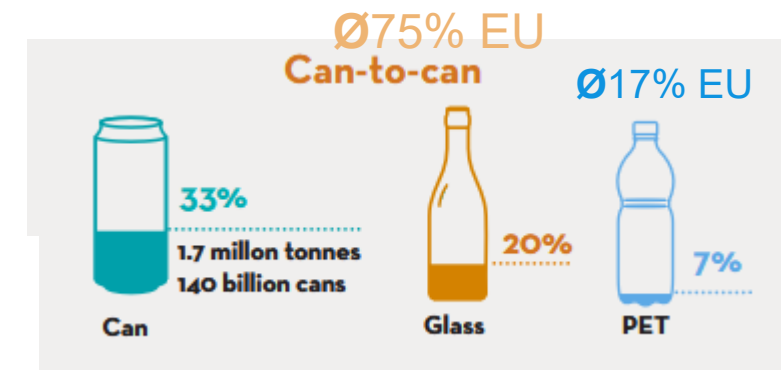
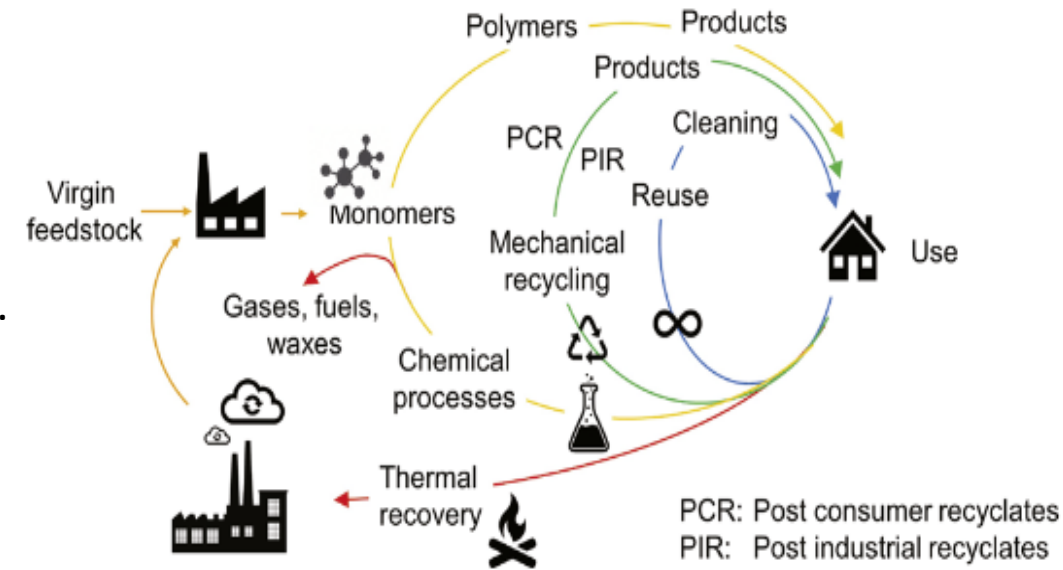
In 2019, 71% of all **aluminium beverage cans** put on the market were recycled –33% back into cans and 38% into other end-uses.

Recycled Paper for Food Packaging

Safety First: Strict chemical testing (MOSH, MOAH, PAHs) means most packaging uses a blend of recycled and virgin materials.

Dry Foods: Approved recycled paper is allowed.

Moist/Fatty Foods: Requires functional barriers (coatings) or pure virgin fibers.



OVERVIEW OF MAJOR RECYCLING TECHNOLOGIES., C. HOPMANN, R. DAHLMANN, M FACKLAM, RECYCLING OF PLASTICS. OCTOBER, 239-273 10.3139/9781569908570.007

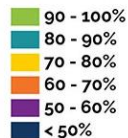
<https://www.recyclingtoday.com/news/steel-packaging-highest-recycling-rate-on-record>

<https://www.verbraucherservice-bayern.de/themen/umwelt/lebensmittelverpackungen-ist-papier-umweltfreundlicher-als-plastik>

[HTTPS://INTERNATIONAL-ALUMINIUM.ORG/WP-CONTENT/UPLOADS/2025/09/CAN-TO-CAN-RECYCLING-FACTSHEET-FINAL.PDF](https://international-aluminium.org/wp-content/uploads/2025/09/can-to-can-recycling-factsheet-final.pdf)

82% Steel Packaging recycling in Europe 2023

(EU 27 + Norway, Switzerland and UK)



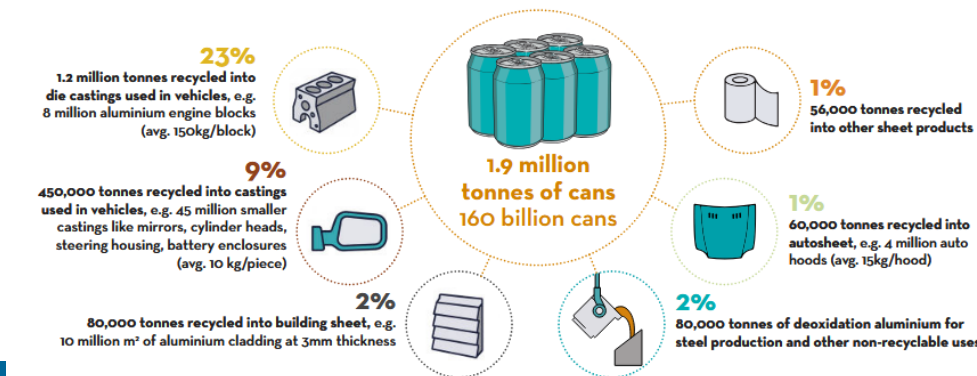
Metal recycling data Hungary

2022 latest official data

Austria, Bulgaria, Croatia, Denmark, Germany, Hungary, Ireland, Latvia, Malta, Netherlands, Norway, Portugal, Slovakia, Slovenia

Source: Official member states and PRO's
Critical Review: Eunomia Research & Consulting Ltd.

38% OF CANS PLACED ON THE MARKET ARE RECYCLED INTO PRODUCTS OTHER THAN CANS



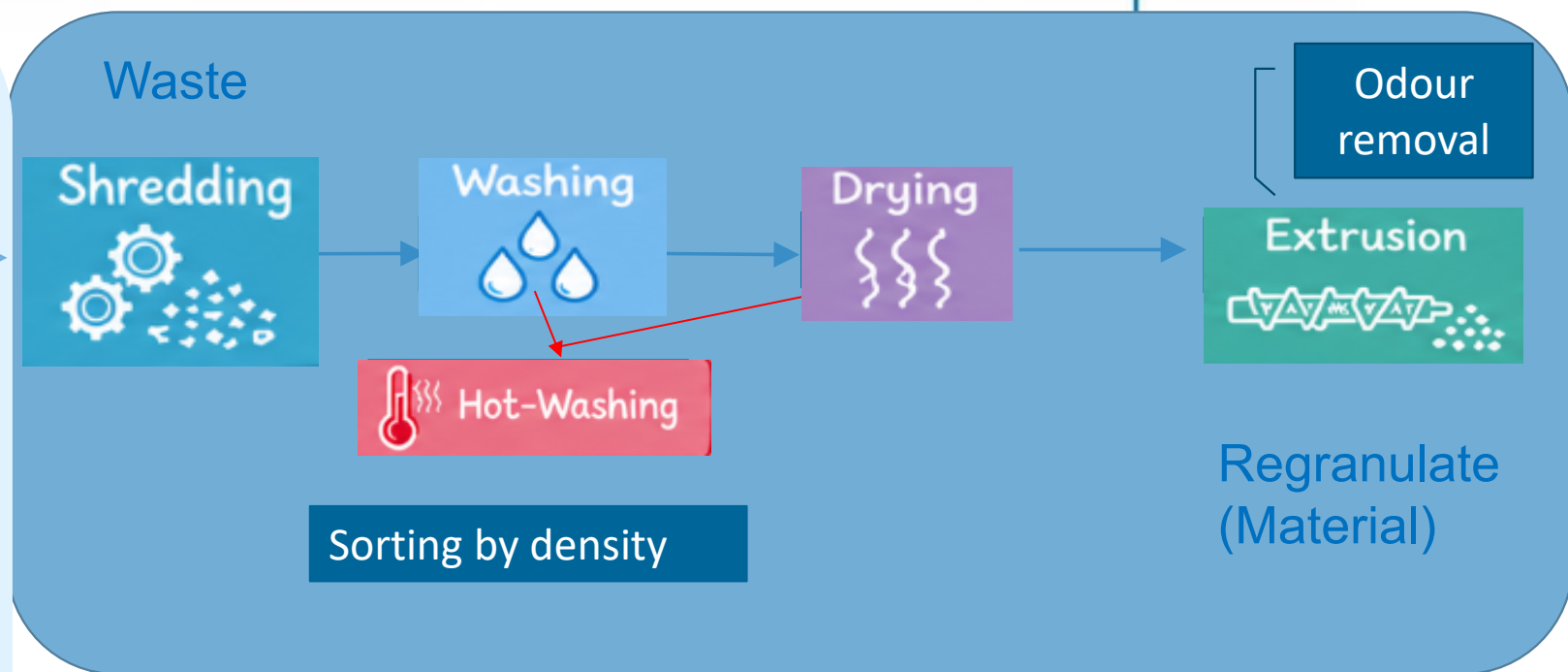
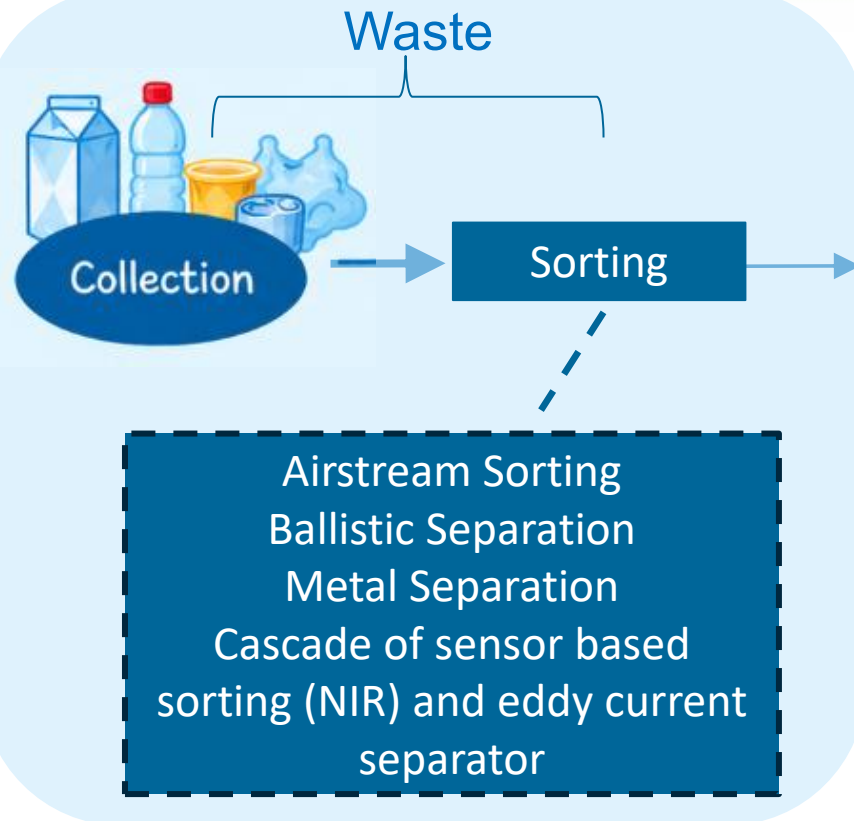
One-third (33%) of all cans put on the market are recycled back into cans, 38% go into other uses, and 29% are not recycled and lost to the aluminium value chain.

Data is derived from University of Tokyo and the IAI project "A Circularity Case for Aluminium Compared with Glass and Plastic (PET)".

Mechanical Recycling

Municipalities → Waste management companies → Sorting companies → Recycling companies

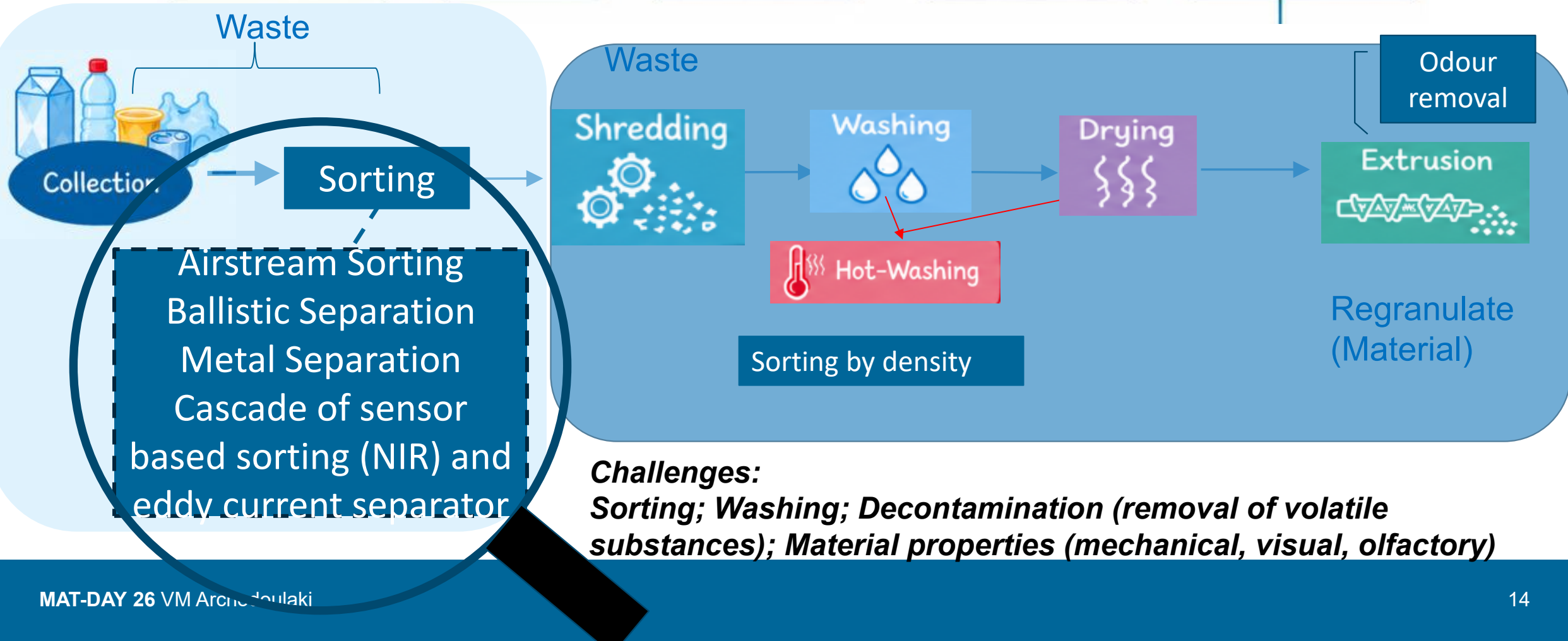
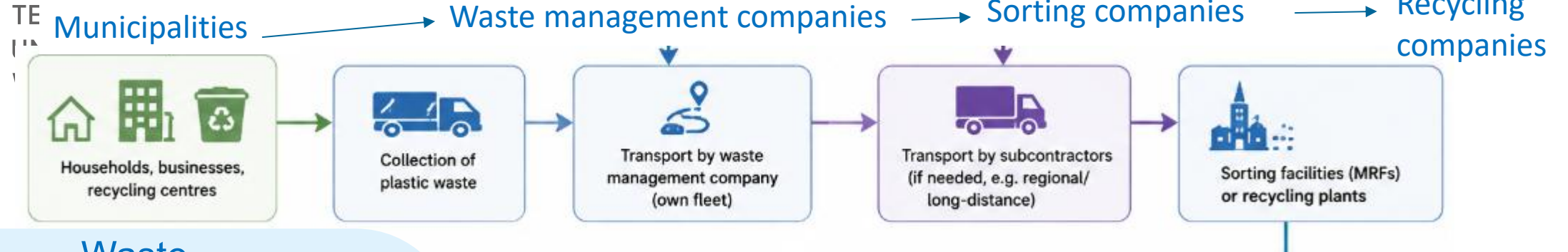
Most probably different



Challenges:

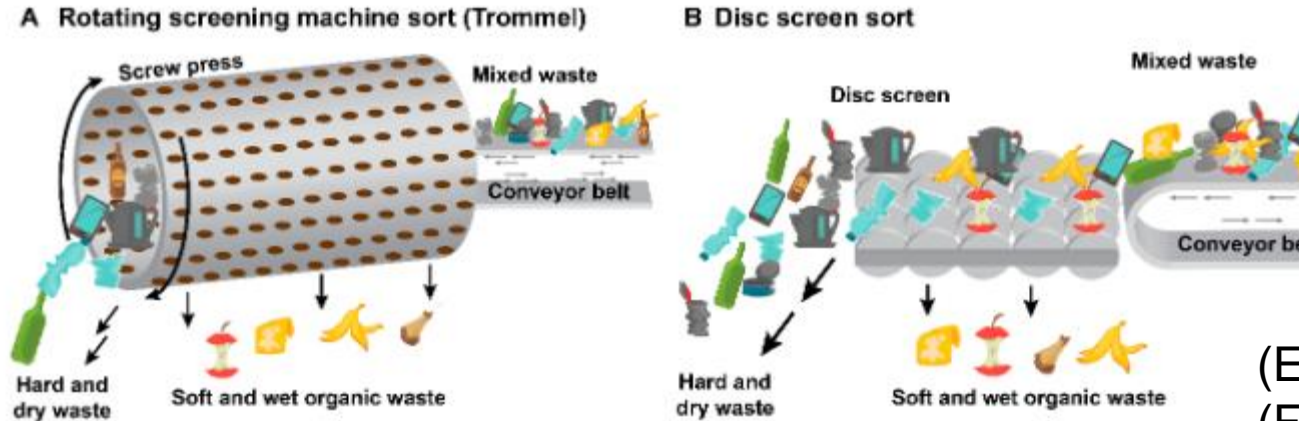
Sorting; Washing; Decontamination (removal of volatile substances); Material properties (mechanical, visual, olfactory)

Mechanical Recycling

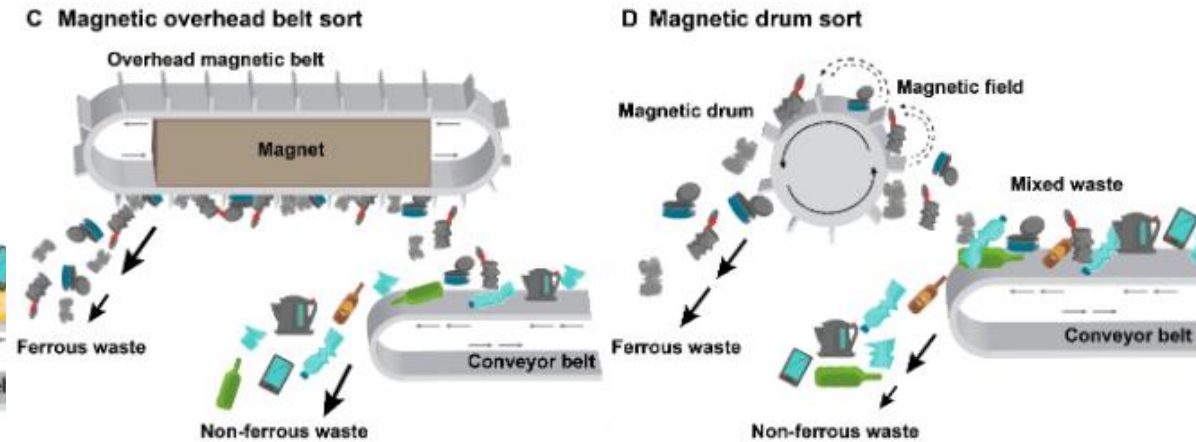


Sorting (mixed waste)

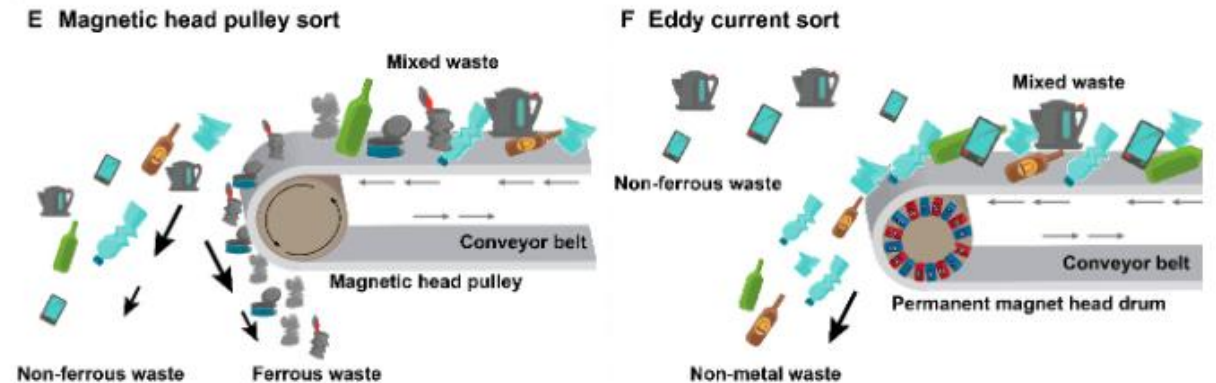
A) rotating screening (trommel) (B) disc screening



(C) magnetic overhead belt (D) magnetic drum



(E) magnetic head pulley; nonferrous metal removal via (F) eddy current separation



Schematic representation of conventional mechanical pretreatment and material recovery technologies also for mixed waste

Sorting

Bag opening: Bags are opened before sorting begins

Screen types: European facilities use **trommel** or rotary screens

Three fractions: Material is split into fines, medium, and coarse

First trommel: Captures 85% to 90% of input packaging material

Second trommel: Receives the material from the 1st screen

Fines separation: The 2nd screen sieves out material < 45 mm

Fines screens: These remove the smallest material (< 20 mm)

from the medium fraction

Medium fraction: Exits the 2nd trommel (45 -220 mm)

combined with the > 20 mm fines fraction

Wind sifters: Separate lightweight flexible plastics and film,

Removes mostly large-format (> 220 mm) PE film

Heavy fraction: Contains rigid plastics, metals, and beverage cartons. The heavy fraction moves to downstream sorting

Wind Sifter, Design purpose: Separates flexible 2D films from heavy 3D containers, uses powerful air suction by rotary fans

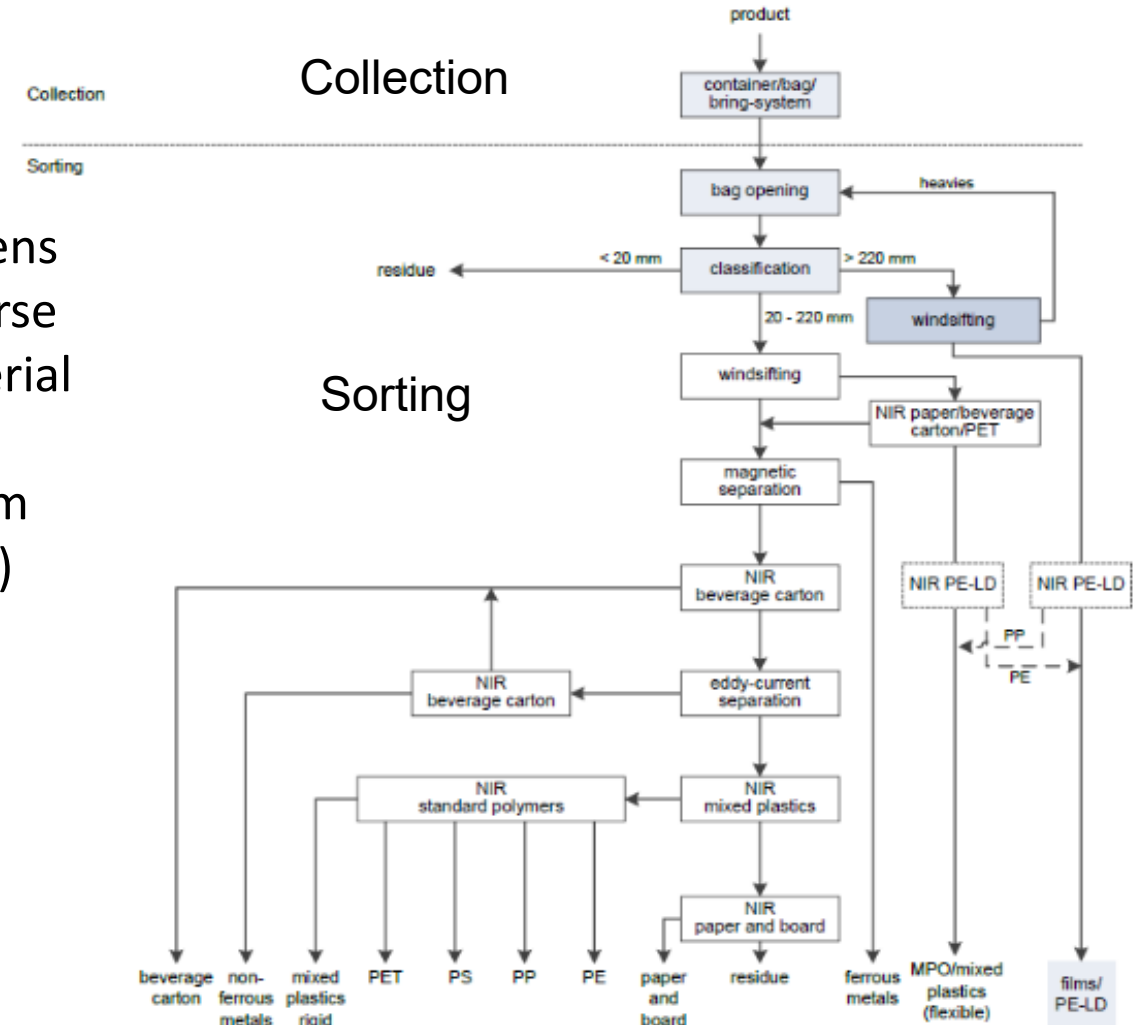


Figure 1: A schematic of a typical Sorting Plant for Light Weight Packaging (LWP) in Germany
Source: Institute cyclos-HTP, (2021)

Optional sorting: NIR-based optical sorting

Bunker storage: Material can go directly to bunkers for baling

Final check: Manual sorting for a final quality control check

Advanced Film Sorting

Color separation: Sorting clear from colored e.g. PE

Material merging: Combines light fractions from the second wind sifter

→The packaging materials has passed through the overhead magnets and eddy current separators to remove ferrous metal and aluminum packaging respectively, materials are sent to a ballistic sorter

Ballistic integration: Merges 2D film materials from ballistic sorters

Final processing: Sends the combined flexible stream to NIR-VIS sorting line

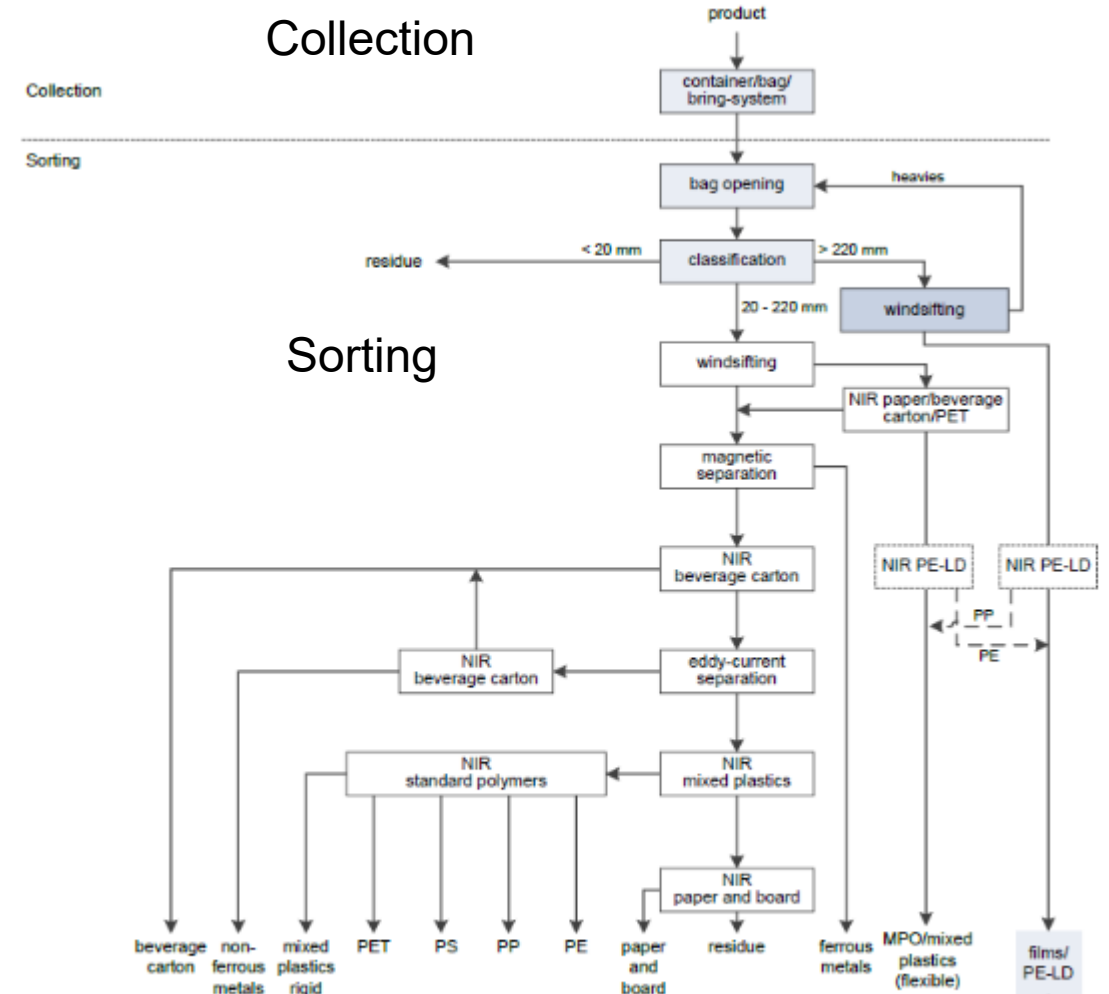
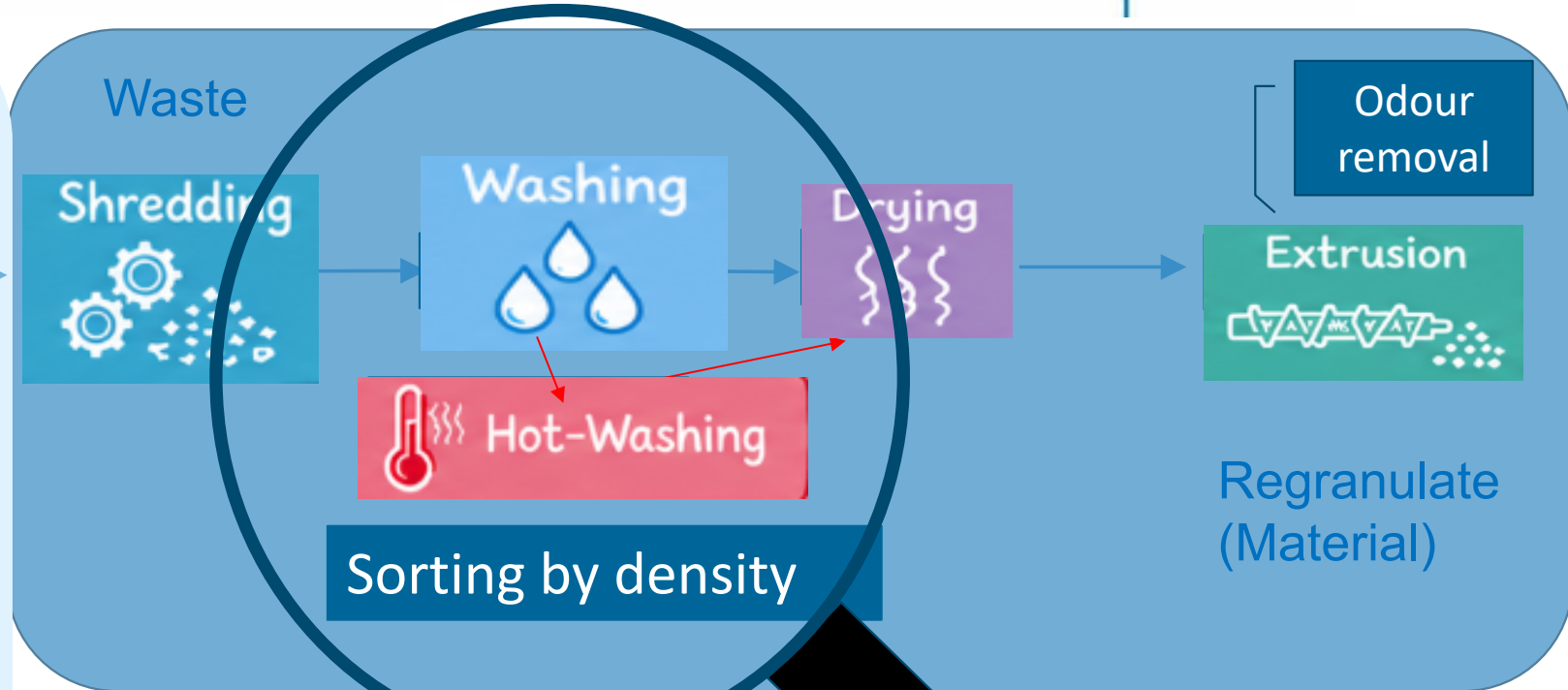
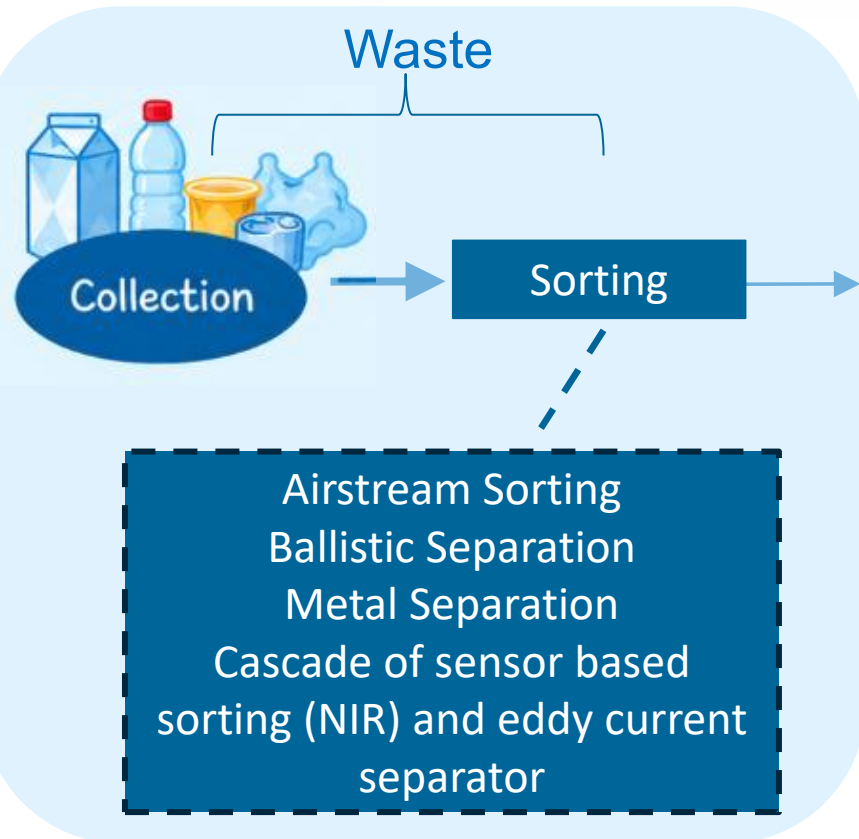
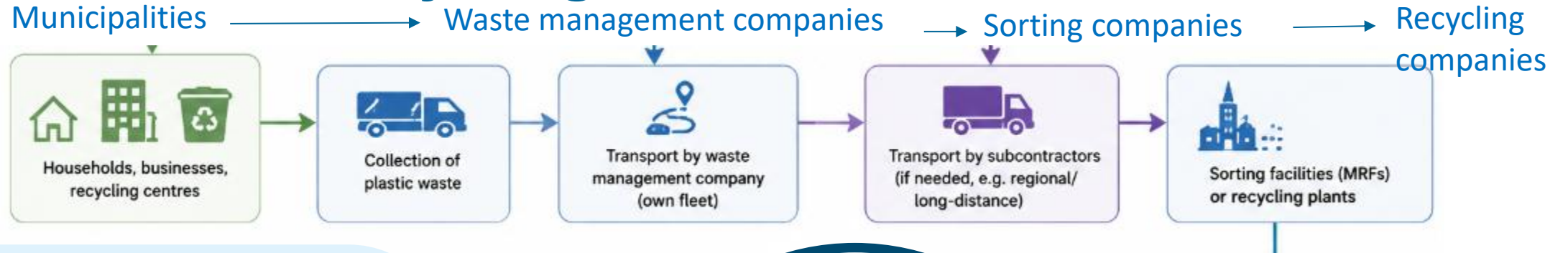


Figure 1: A schematic of a typical Sorting Plant for Light Weight Packaging (LWP) in Germany
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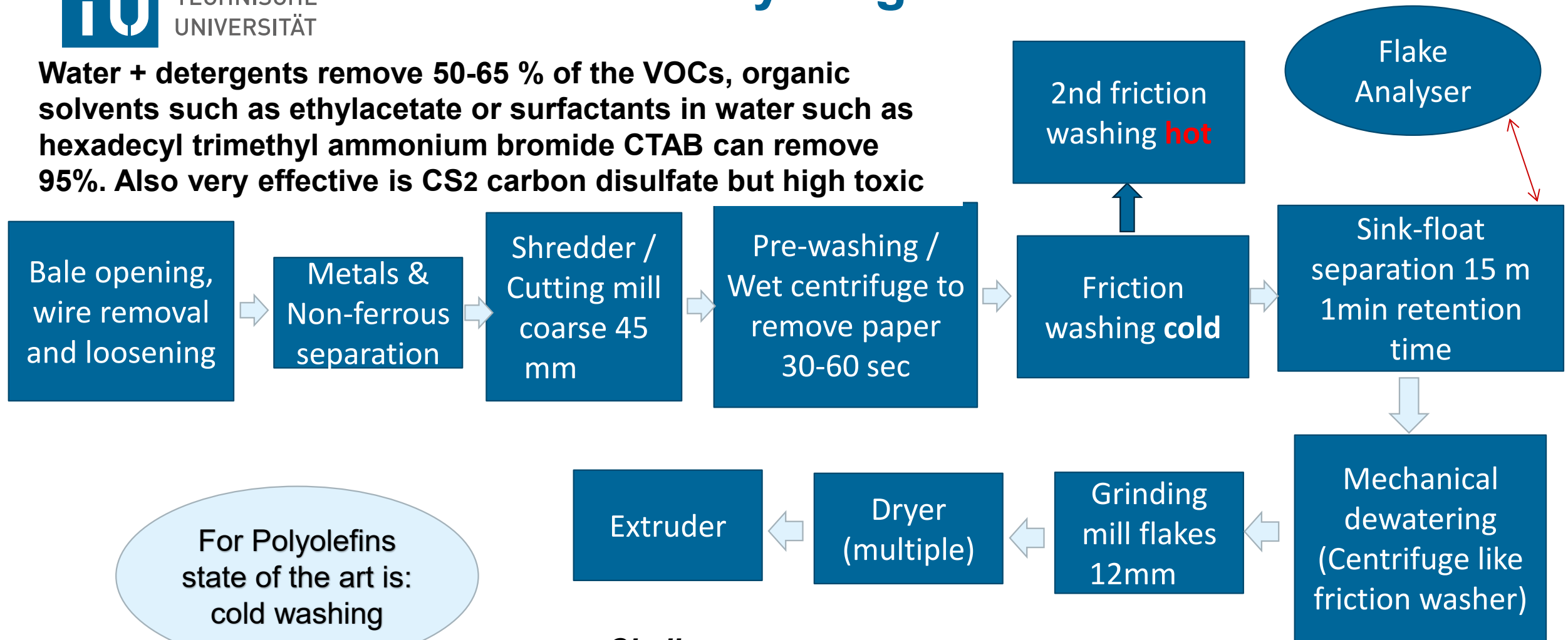
Mechanical Recycling



Challenges:
 Sorting; Washing; Decontamination (removal of volatile substances); Material properties (mechanical, visual, olfactory)

Mechanical Recycling

Water + detergents remove 50-65 % of the VOCs, organic solvents such as ethylacetate or surfactants in water such as hexadecyl trimethyl ammonium bromide CTAB can remove 95%. Also very effective is CS₂ carbon disulfate but high toxic



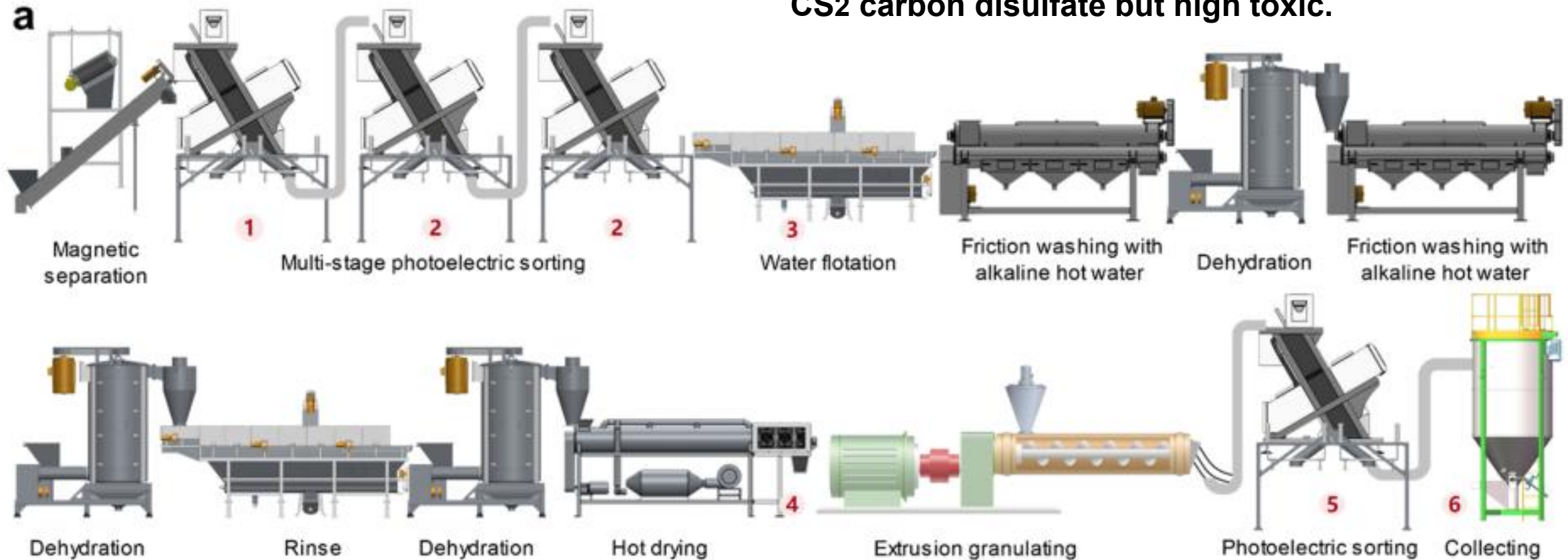
For Polyolefins
state of the art is:
cold washing

Challenges:

Sorting; Washing; Decontamination (removal of volatile substances); Material properties (mechanical, visual, olfactory)

Optimizing Recycling

Water + detergents remove 50-65 % of the VOCs, organic solvents such as ethylacetate or surfactants in water such as hexadecyl trimethyl ammonium bromide CTAB can remove 95%. Also very effective is CS₂ carbon disulfate but high toxic.



L. DONG, W. ZHI, W. LI, J. LI, *OPTIMIZING THE RECYCLING PROCESS OF PP PLASTICS FROM WASTE WASHING MACHINES: SUSTAINABLE STRATEGY FOR ENVIRONMENTALLY FRIENDLY REUTILIZATION*, 2024, ACS SUSTAINABLE RESOURCE MANAGEMENT, [HTTPS://DOI.ORG/10.1021/ACSSUSRESMGMT.4C00101](https://doi.org/10.1021/acssusresmgmt.4c00101)

Who pays for which waste



ANY WASTE THAT CAN'T
BE REUSED



VIENNA'S ORGANIC WASTE BIN
IS VEGAN

local authorities on fee-
based financial support



CLEAN PAPER AND SMALL
CARDBOARD PACKAGING



ALL PACKAGING EXCEPT
PAPER AND GLASS



LIGHTLY TINTED GLASS
GOES IN THE COLOURED
GLASS CONTAINER

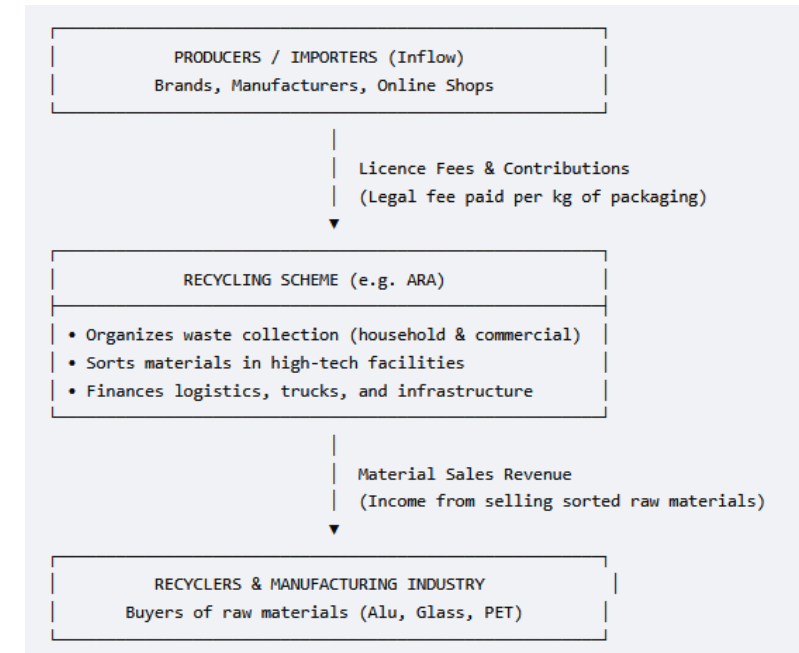
Collecting systems (e.g. ARA) from
extended producer responsibility &
revenues from secondary raw materials

IMAGES: [HTTPS://WWW.WIEN.GV.AT/PDF/MA48/FLUGBLATT-GETRENNTE-SAMMLUNG-EN.PDF](https://www.wien.gv.at/pdf/MA48/FLUGBLATT-GETRENNTE-SAMMLUNG-EN.PDF)

Financial Flow of Packaging Recycling Systems

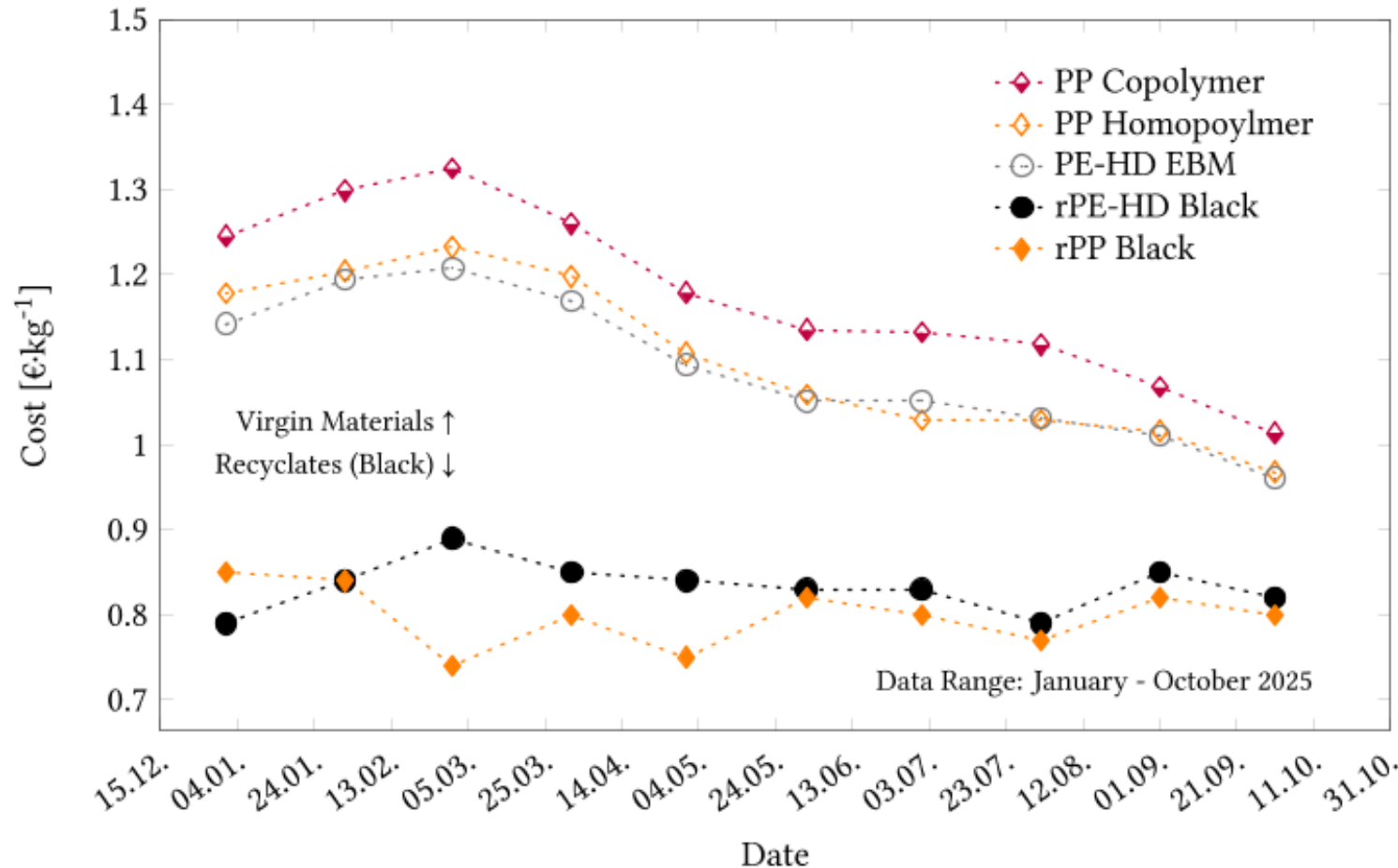
Material Category	Rates €/kg	Characteristics / Background
Paper, commercial Paper, households	0.07 0.19	Cost-effective, highly recyclable
Ferrous metal, commercial households	0.07 0.45	Easy to separate
Aluminium, commercial Aluminium Households	0.09 0.48	Valuable material, generates high sales revenue
Foils, commercial	0.18	highly complex sorting
Moulded containers, commercial	0.1	highly complex sorting
EPS, commercial	0.35	
Plastic households	0.99	highly complex sorting

[HTTPS://WWW.ARA.AT/UPLOADS/DOKUMENTE/TARIFBL%C3%A4tter/ARA-TARIFF-RATES-2025.PDF](https://www.ara.at/uploads/dokumente/tarifbl%C3%A4tter/ARA-TARIFF-RATES-2025.PDF)



- **Funding Disposal:** The fee finances collection, sorting, and recycling of packaging waste distributed by companies.
- **Legal Compliance ("Release from Obligation"):** Companies are legally required to take back their used packaging. Paying the ARA fee transfers this duty to the ARA collection system.

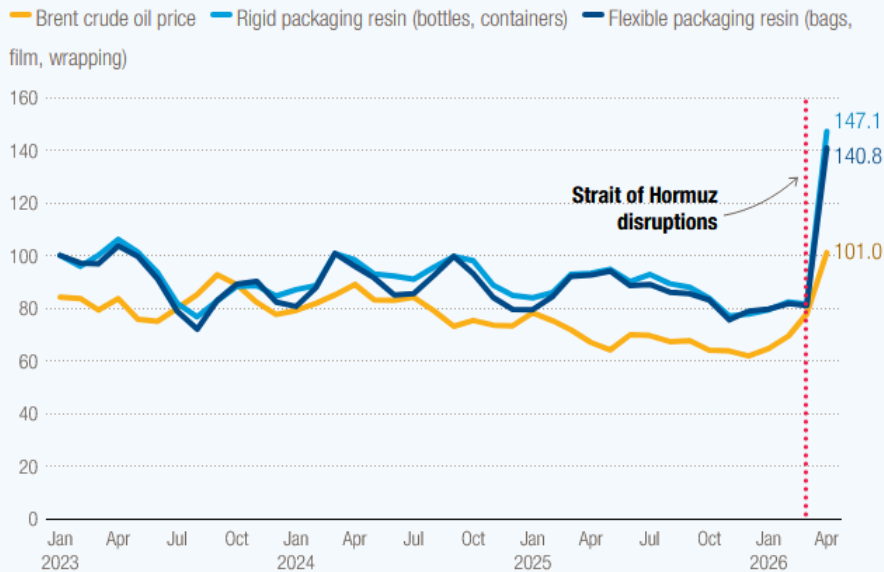
Market Prices



Cost of virgin resins and black-coloured regranulates (“Qualität Regranulat Schwarz”) according to the “Market Prices for Commodities in Central and Eastern Europe” between January and October 2025. Regranulates (rPP, rPE-HD) and virgin materials (PP, PE-HD) are labelled by solid and hollow markers, respectively

➤ Strait of Hormuz disruptions send oil and plastics prices soaring

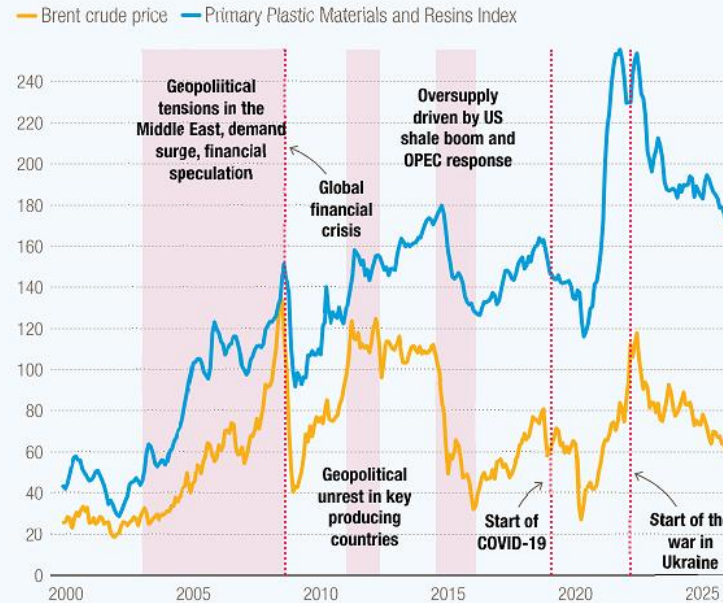
Plastic resin indexes, index 2023=100 and Brent crude oil price, dollars, January 2023 – April 2026



Source: UN Trade and Development (UNCTAD), based on LSEG data and analytics.
Note: Rigid packaging resin refers to HDPE; flexible packaging resin refers to LLDPE.

➤ The oil-plastics price link: 25 years of evidence

Primary plastic materials and resins index, index 1980=100 and Brent crude oil prices, dollars, December 1999 – February 2026



Source: UN Trade and Development (UNCTAD), based on U.S. Bureau of Labor Statistics via FRED (Producer Price Index by Industry: Plastics Material and Resin Manufacturing Primary Products: PCU325211325211P) and the World Bank (Pink Sheet).

Environmental Costs: plastic recycling extends beyond immediate financial returns. By reducing landfill and pollution, recycling mitigates environmental externalities, which can translate into long-term economic benefits through improved public health and ecosystem services.

Supply Chain: A well-functioning European recycling sector strengthens our resilience against global supply shocks and increases sources security.

Supply Chain: Collection, sorting, and processing of plastic involve multiple stakeholders, each impacting costs and efficiency.

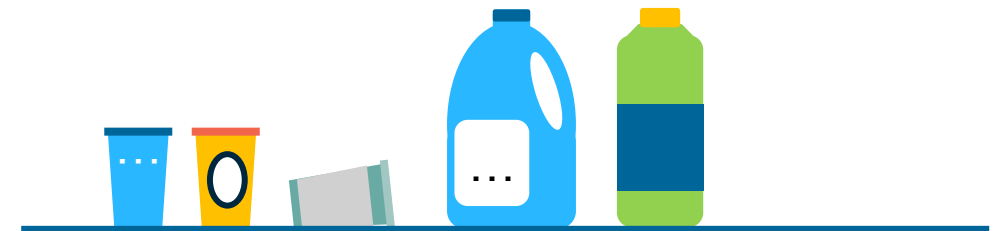
Cost-Effectiveness: Plastic recycling often costs more than producing virgin plastic, making economic viability dependent on scale, technology, and market demand

Challenges in sorting

- **Recovery of sorted fractions**
- Packaging design makes separation difficult (printing, labels, closures)
- Multiple sorting is limited due to disposal prices
- Manual re-sorting is often labour-intensive and costly

- **Automatic separation by plastic type (theoretical possible by container size)**
 - Cup (thermoformed / injection moulded)
 - Bottles (blow-moulded)
 - Bins (injection moulded)

} e.g.: PP



Challenges in sorting

Made for functionality and not for recycling

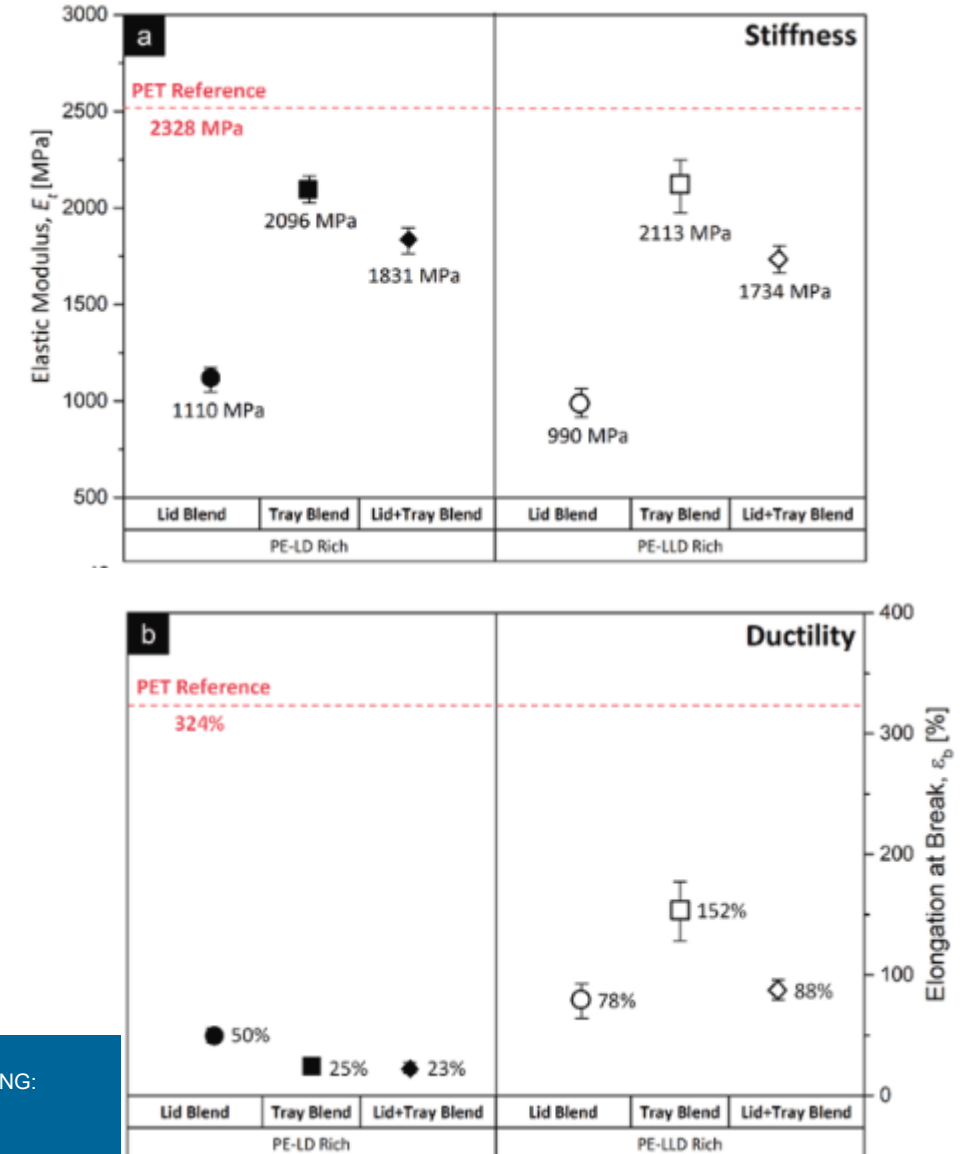
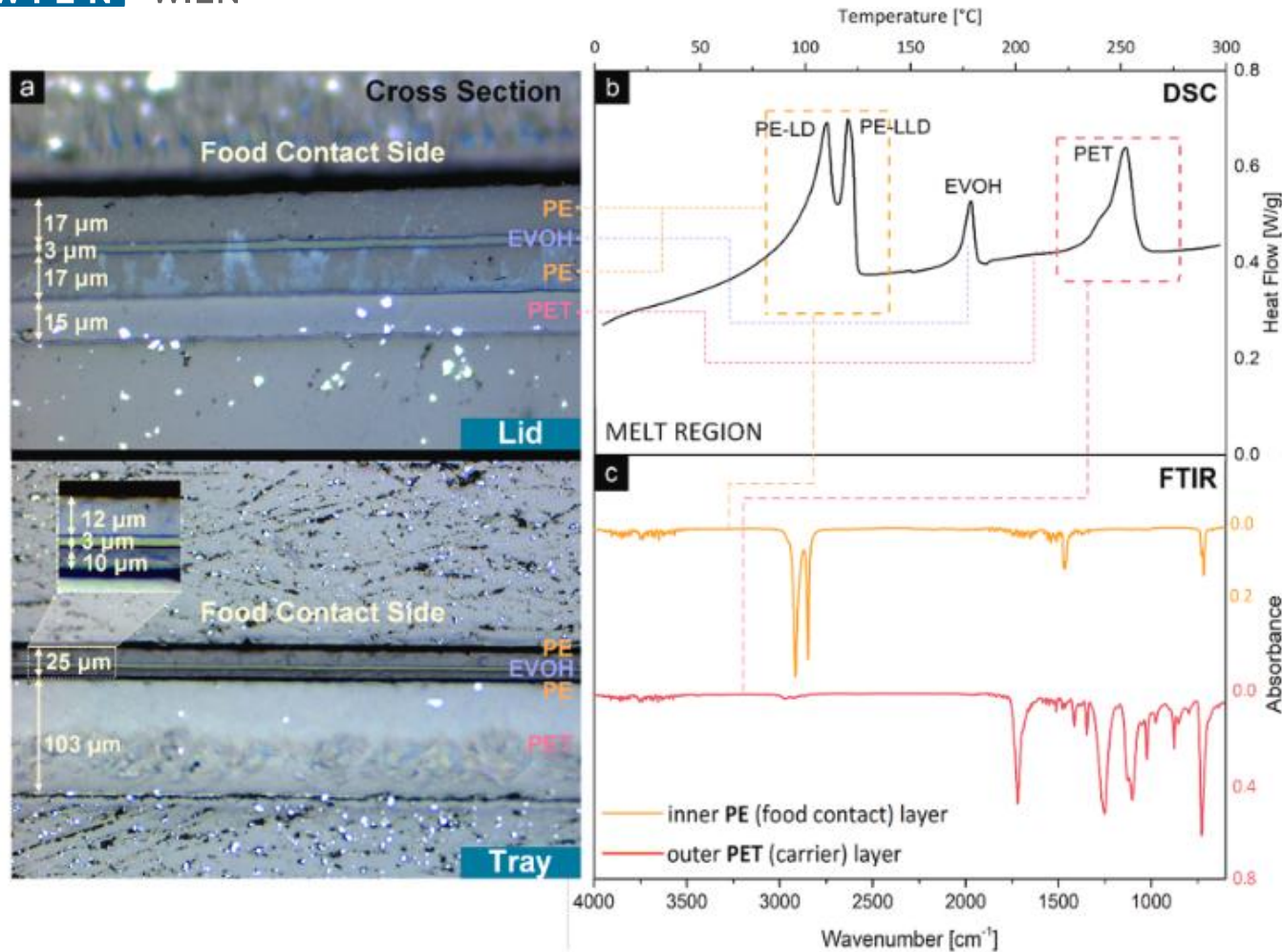
- 50 wt.% filling content
 - Mainly Magnesium
- Black color hinders proper NIR detection
- Density change due to fillers
 - Swim-sink separation not effective
- Unfortunately, not built for recycling
- **Design4Recycling is important!**



© ISABELLE GENTGEN

Challenges in recycling of multilayer packaging

60 individual post-consumer MAPs
(30 sausage/cheese packaging)



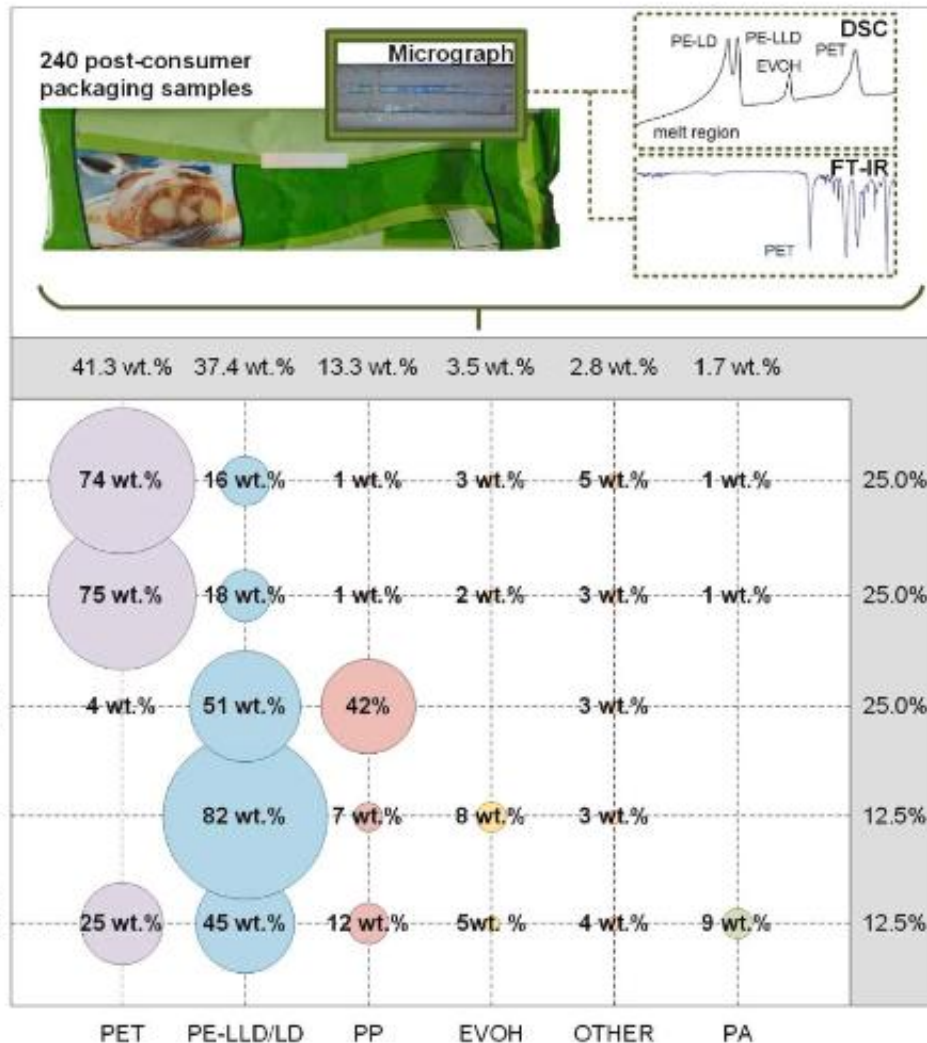
PET-PE immiscibility resulted in phase separation causing inhomogeneity

Challenges in recycling of multilayer packaging

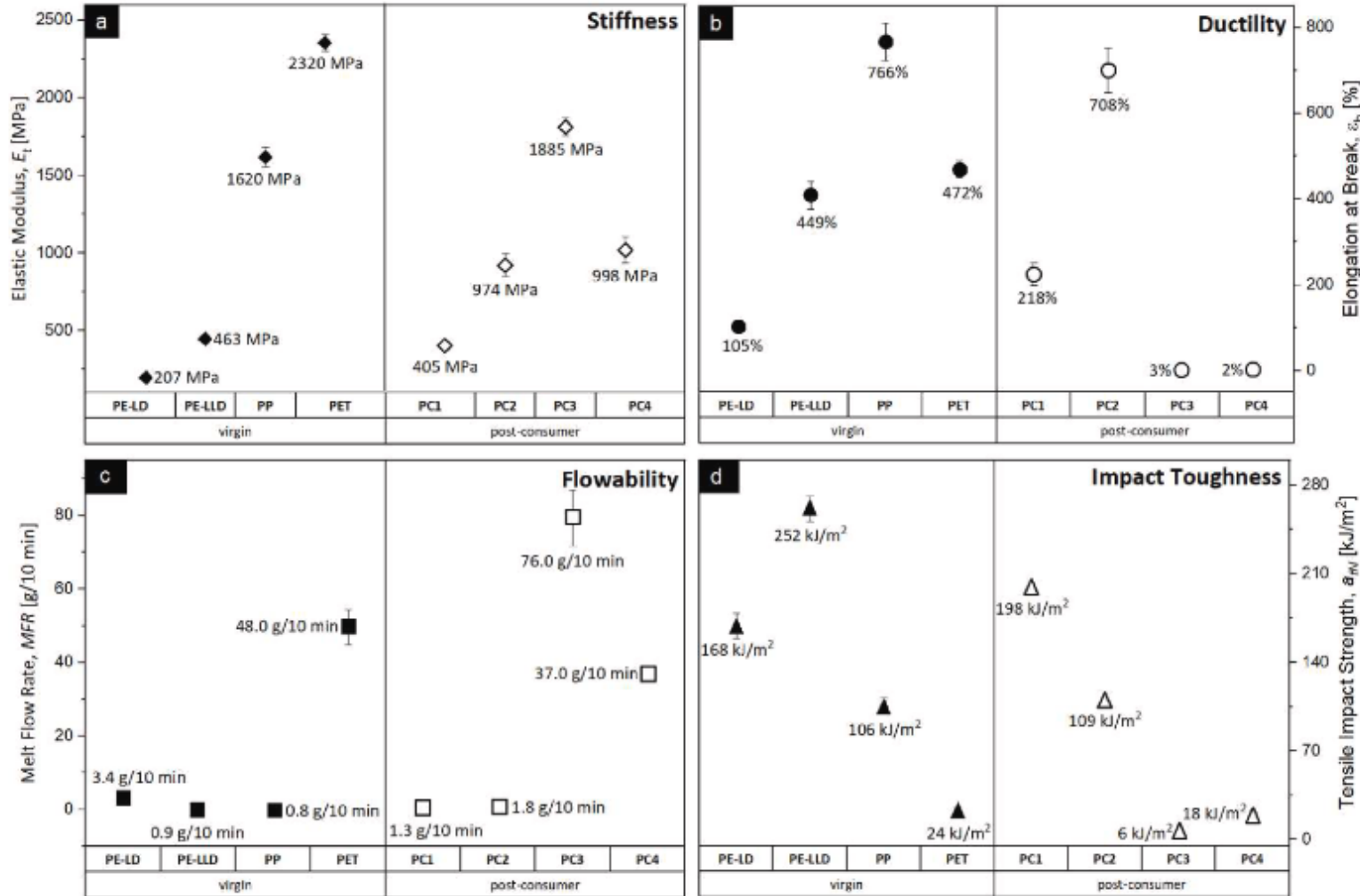
Composition and layer thicknesses of different 4-layer films commercially used for the packaging of ham slices comprising three similar layers (PE-EVOH-PE) but using paper, PP, PET or PA as a fourth layer.

	Layer 1	Layer2	Layer 3	Layer 4	Shelf-life
Paper/PE/EVOH	50 µm paper	25 µm PE	4 µm EVOH	20 µm PE	4 weeks
PP/PE/EVOH	22 µm PP	20 µm PE	5 µm EVOH	23 µm PE	5 weeks
PET/PE/EVOH	17 µm PET	23 µm PE	4 µm EVOH	20 µm PE	5 weeks
PA/PE/EVOH	22 µm PA	25 µm PE	6 µm EVOH	25 µm PE	4 weeks

Post-consumer waste **stream sample composition** of packaging derived from structure analysis (240 samples) and separated by product packaging category (cured meats, sliced cheese, frozen food, tubes, snacks and ready-made meals) and polymer type (PET, PE-LLD/LD blend, PP, EVOH, OTHER minor components and PA). Polymer type shares are given in wt.% while the category shares are packaging count shares.



Challenges in recycling of multilayer packaging

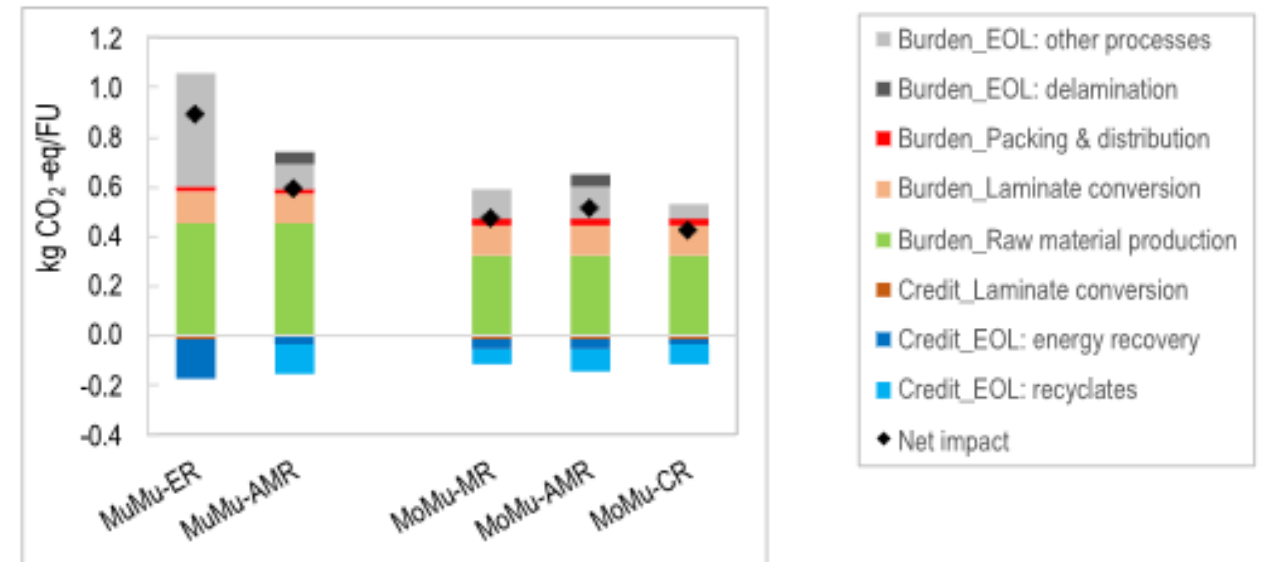


(a) Elastic modulus E_t [MPa],
(b) elongation at break ϵ_b [%],
(c) melt flow rate MFR [g/10 min]
and (d) tensile impact strength
atN [kJ/m²] of common post-
consumer packaging blends
comprising
PE-LD/PE-LLD/EVOH 'PC1',
PE-LD/PE-LLD/PP/EVOH 'PC2',
PET/PE-LD/PE-LLD/EVOH 'PC3'
and
PET/PE-LD/PE-LLD/PP/
EVOH 'PC4' (hollow markers)
compared to virgin mono-material
references (solid markers)

Packaging	Packaging structure	Studied scenarios
Current MuMu packaging	- Printed BOPA layer - Solvent-based adhesive - PEP layer (PE-EVOH- PE) - Surface weight: 113.6 g/m² - Thickness: 119.0 μm	- Current: MuMu with incineration with energy recovery (MuMu-ER) - Emerging: MuMu with advanced mechanical recycling through delamination-deinking (MuMu-AMR)
MuLa		
Alternative MoMu (PE-based) packaging	- Printed MDOPE layer - Solvent-free adhesive - PEP layer (PE-EVOH-PE) - Surface weight: 138.4 g/m² - Thickness: 148.5 μm	- Current: MoMu with conventional mechanical recycling (MoMu-MR) - Emerging: MoMu with advanced mechanical recycling through delamination-deinking (MoMu-AMR) - Emerging: MoMu with chemical recycling (MoMu-CR)
MoLa		

(Multilayer-vs.-Monomaterial-Dilemma = Lightweighting vs. Recycling)

(a) Climate change impact



Shifting from MuLa to MoLa reduces impacts on 3 of 4 key categories: climate change, particulate matter, photochemical ozone formation, and the single score (aggregated 16 categories). These **benefits** primarily stem from raw material production and end-of-life management, **where recycling replaces incineration with energy recovery, despite MoLa being heavier (22%)**

Conventional vs. Biodegradable

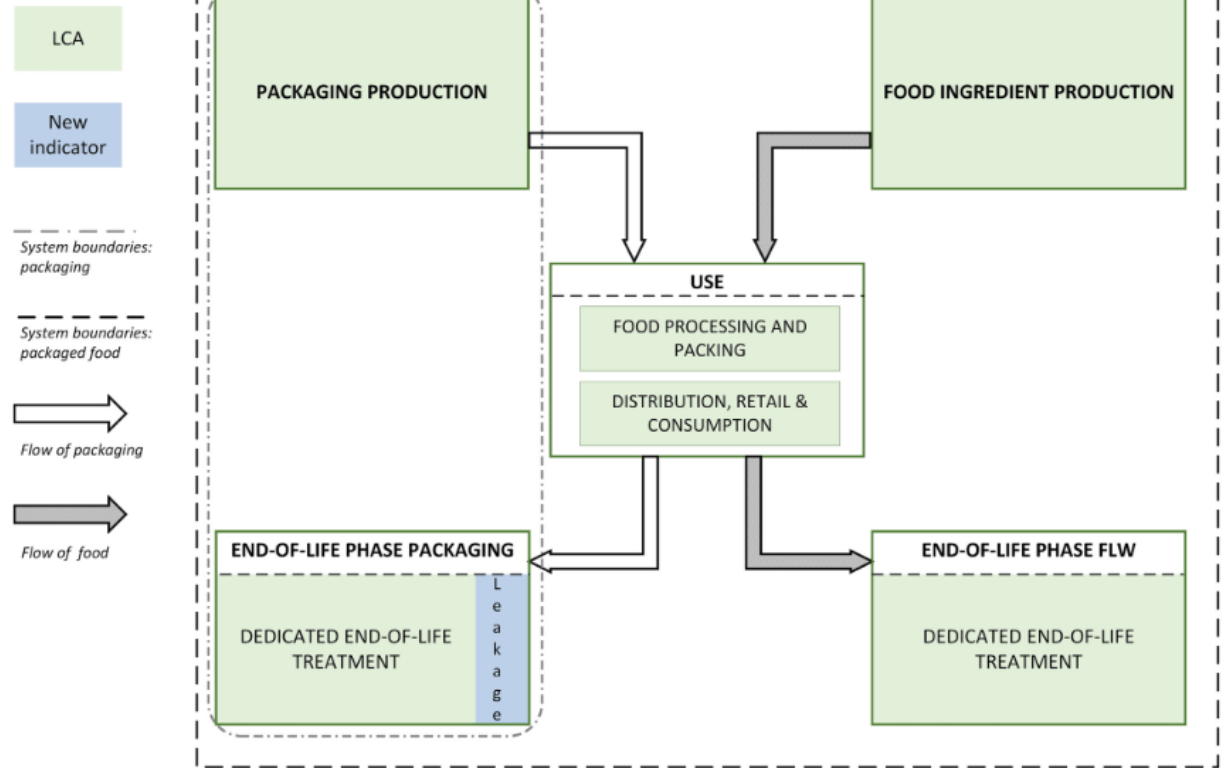
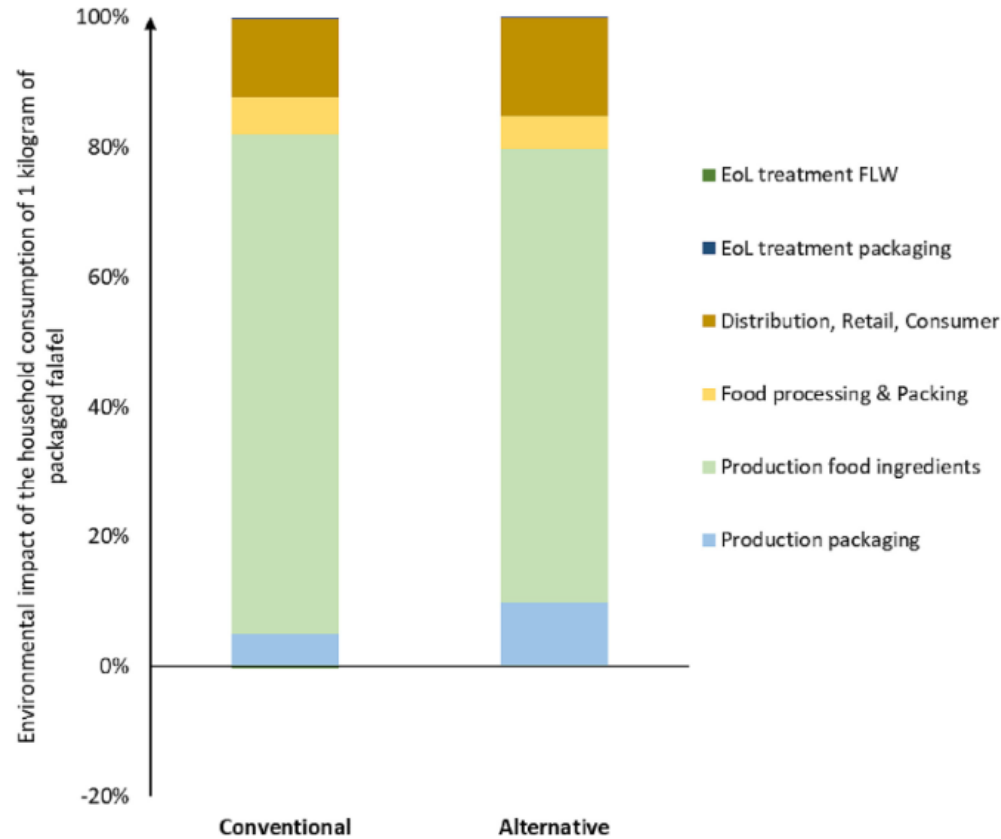


Fig. 1. Simplified process scheme of the life cycle of packaged food, with an indication of potential evaluation by classical LCA and the newly developed indicator. This indicator only focuses on the marine litter impact. The system boundaries for the evaluation of (1) the packaged food product and (2) only the packaging (i.e. primary packaging) are indicated. FLW = food loss and waste; LCA = life cycle assessment.

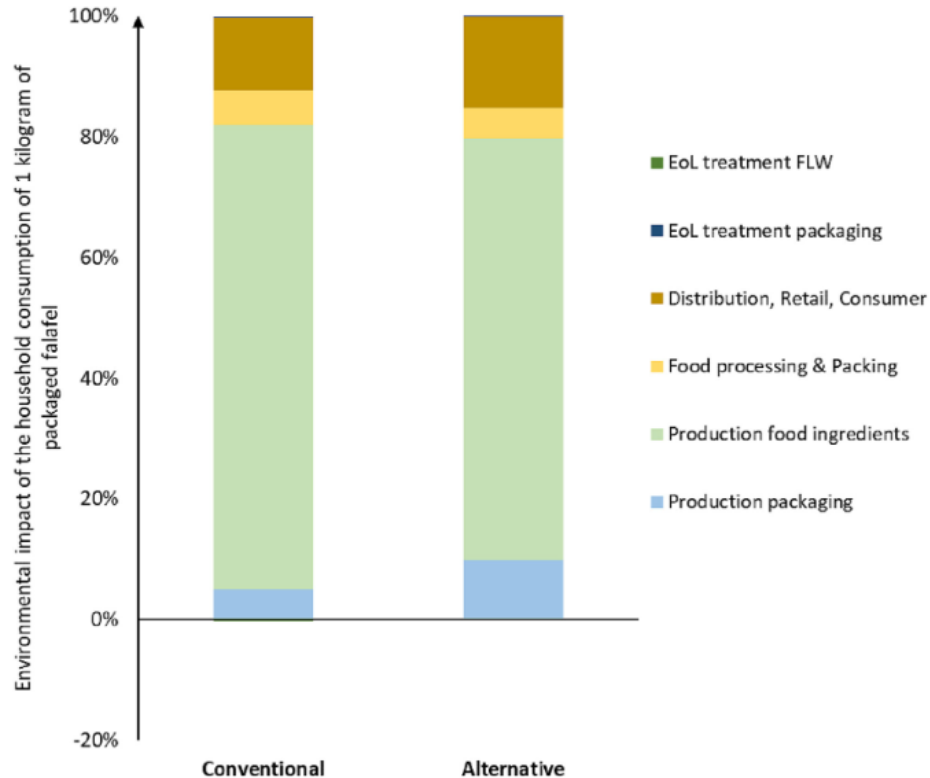
Composition, mass, dimensions and dedicated end-of-life (EoL) treatment of conventional and alternative primary packaging. INC, incineration; REC, recycling; PHBV, Poly(3-hydroxybutyrate-co-3-hydroxyvalerate); PP, polypropylene.

	Packaging component	Composition	Mass (g/kg falafel)	Dimensions tray (mm × mm × mm)	EoL scenario*
Conventional	Tray	PP	61.3	187 × 137 × 25	REC
	Film	multilayer PP	10.0		INC
Alternative	Tray	PHBV	120.5	187 × 137 × 37	INC
	Film	PHBV	13.3		INC

* includes collection and sorting (in case of recycling scenario) as well.

Contribution of the different life cycle stages to the environmental impact considering the conventional and alternative packaging. The functional unit (FU) corresponds to the household consumption of 1 kg packaged falafel.

Conventional vs. Biodegradable



Contribution of the different life cycle stages to the environmental impact considering the conventional and alternative packaging. The functional unit (FU) corresponds to the household consumption of 1 kg packaged falafel.

Table 3

Potential marine litter formation (g) and lifetime costs on marine ecosystem services (ES) (EUR₂₀₂₀) per household consumption of 1 kg packaged falafel (functional unit, FU) in conventional (PP) and alternative (PHBV) packaging, assuming waste collection in EU-28. P_E , the probability for plastic waste collected in EU-28 to become marine litter.

	Conventional packaging	Alternative packaging
Mass of the tray per FU (g)	65.9	129.5
P_E (%)	$2.0E-02$	$2.0E-02$
Potential marine litter formation (g/FU)	$1.3E-02$	$2.6E-02$
Lifetime costs on marine ES, best case scenario (EUR ₂₀₂₀ /FU)	$1.9E-03$	$2.8E-04$
Lifetime costs on marine ES, worst case scenario (EUR ₂₀₂₀ /FU)	$1.9E-02$	$2.8E-03$

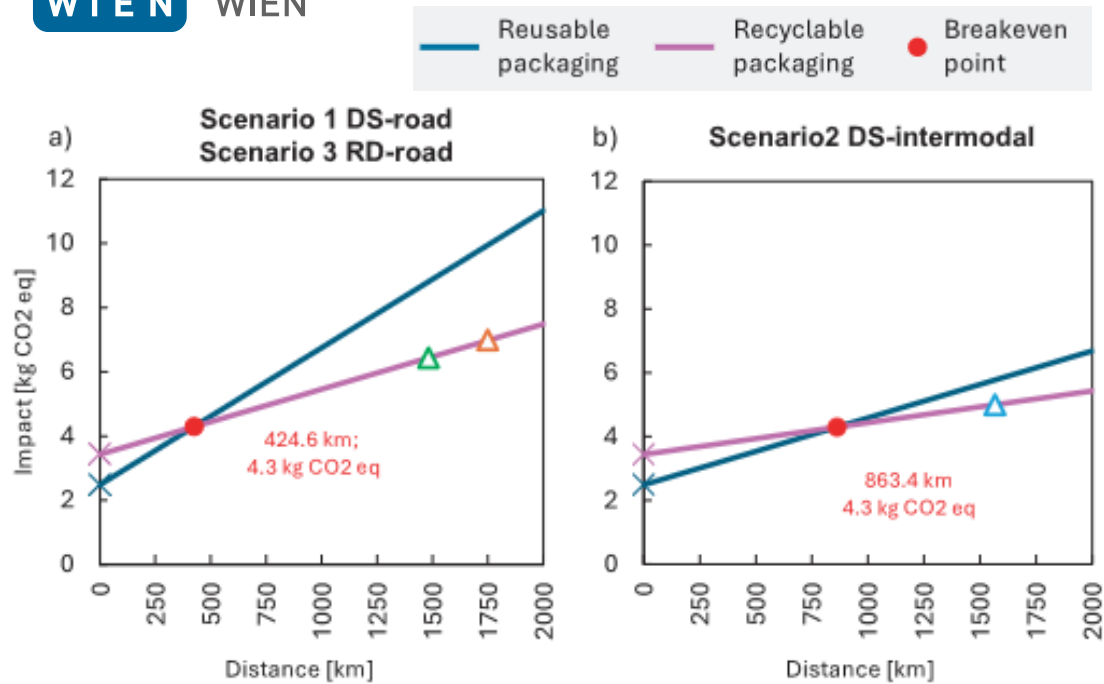
the lifetime costs for marine ES are about seven times lower, and this despite its higher mass

Composition, mass, dimensions and dedicated end-of-life (EoL) treatment of conventional and alternative primary packaging. INC, incineration; REC, recycling; PHBV, Poly(3-hydroxybutyrate-co-3-hydroxyvalerate); PP, polypropylene.

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	Film	PHBV	13.3		INC

* includes collection and sorting (in case of recycling scenario) as well.

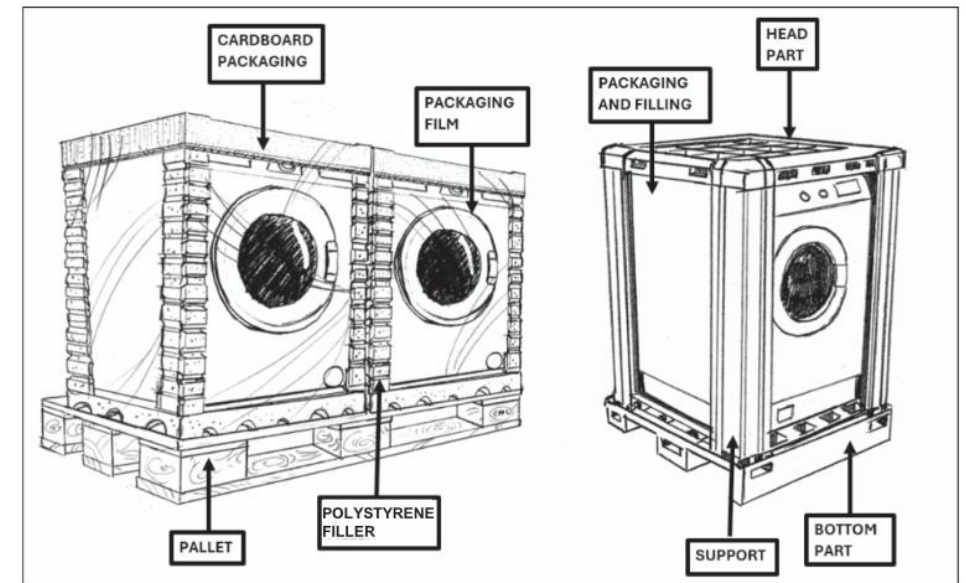
Recycling vs. Reusable



Breakeven point analysis results referred to the functional unit of this study (1 appliance delivery), calculated considering Climate Change as the reference impact category a) the Scenario 1 direct sales-road and Scenario 3 retail distribution-road, b) the Scenario 2 DS-intermodal, rail transport for long-distance segments + lorry transport for domestic delivery.

The LCA considers production, use, and end-of-life phases, with Climate Change as the reference impact category. Results show that recyclable packaging generally has a lower environmental impact, except for short transport distances (below 425 km for road transport and below 750 km for intermodal transport).

REC 1.14 kg vs. REU 14.34 kg



Closed loop vs. Open loop



Fraction PET
Fraction PE+PP
(= no further recycling
INSINERATION)

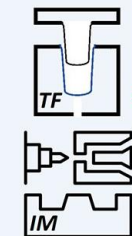
Fraction PET
• separated sorting
• **simple** design
• Washing
• Adjustment of the molar mass during the process



PE cap

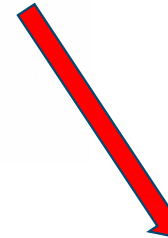
PET Bottle

PP wrap-around labels



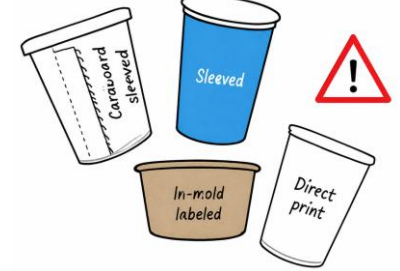
Different POLYMERS &
ADDITIVES & PROCESSING
TECHNOLOGIES

Mitigation
• Prior-Sorting



Decoration (**diverse** design)

- Labels
- Sleeves
- Paper
- IML
- Adhesives
- *Direct Printing (Pigments)*



Mitigation

- Prior-Sorting
- De-Lebeling
- De-Sleeving
- Washing
- De-Inking

Mitigation

- Prior-Sorting
- Washing
- Additional: Removal of volatile substances



Shredded labels (Foto: J. Schlossnikl)

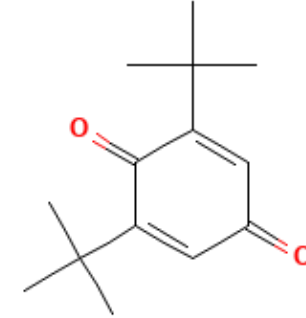
Chemical and biological results

- The substances found were classified into Cramer classes
- Cramer Class I (low toxicity)
- Cramer Class II (moderate toxicity)
- **Cramer Class III (highly toxic) (21% of the identified substances)**
- 71 substances could be classified, whilst 95 substances remained unidentifiable

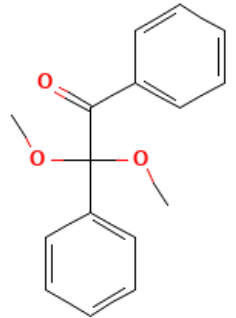


Labels are important for information transfer

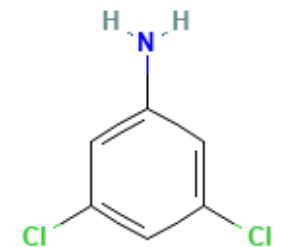
- Labels are screening out critical substances → incineration
- With good detachability, good recyclability of the remaining packaging



2,6-ditert-butylcyclohexa-2,5-diene-1,4-dione



2,2-dimethoxy-1,2-diphenylethanone



3,5-dichloroaniline

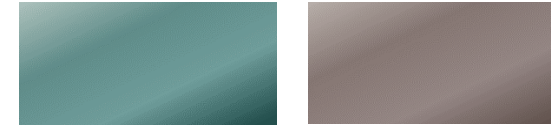
Challenges regarding material properties

- **Potential reduction of the mechanical properties**

- Ductility ↓
- Stress crack resistance ↓

- **Variable colour of the recycled material**

depending on the colour composition of the waste stream



- **Substances that could pose a risk to human health**

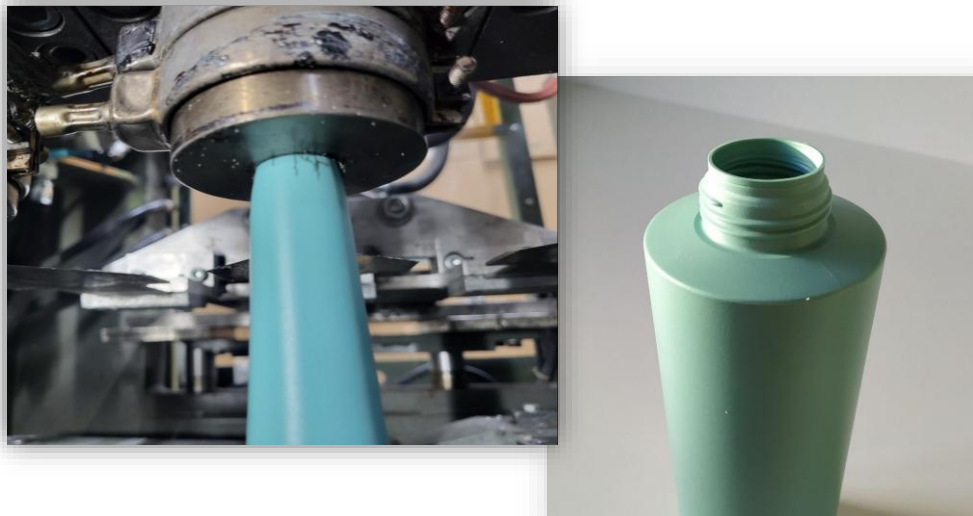
e.g. from decorative elements that do not need to be food-safe



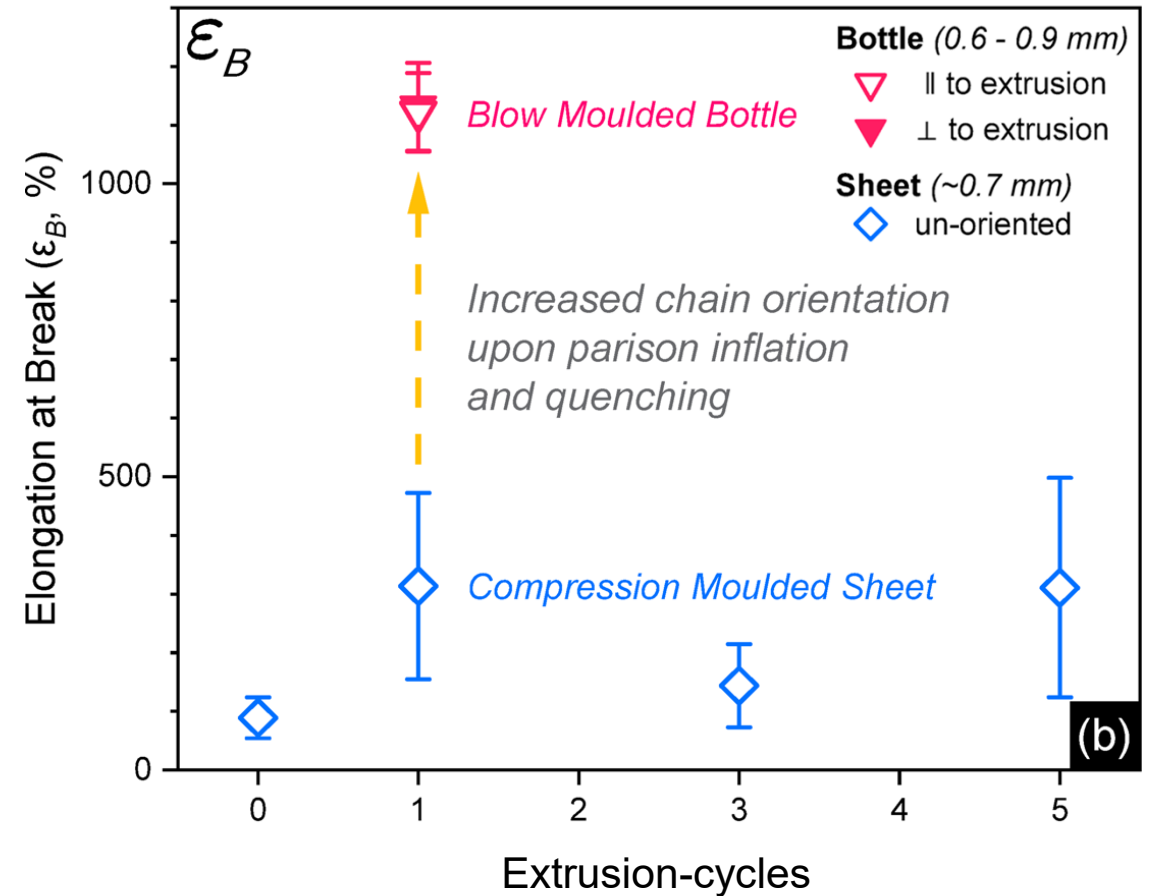
Fotos: Lorenz Bichler

Mechanical properties 100% rPE-HD

- Bottles retain high ductility despite PP contamination below 5 wt%
- No indications of major thermomechanical damage from repeated extrusion



Preform and bottle made of cold-washed rHDPE; Source: Fa. Sauer (right), L. Bichler (left)



Mechanical properties 100% rPE-HD

- **Drop test**
- Testing of recycled and standard PET bottles (4 of each)
- Filled with water as the test medium (“initial weight” ~ 1090 g)
- 80 cm drop height
- No failure even after (up to 3) repeat tests

Current challenges:

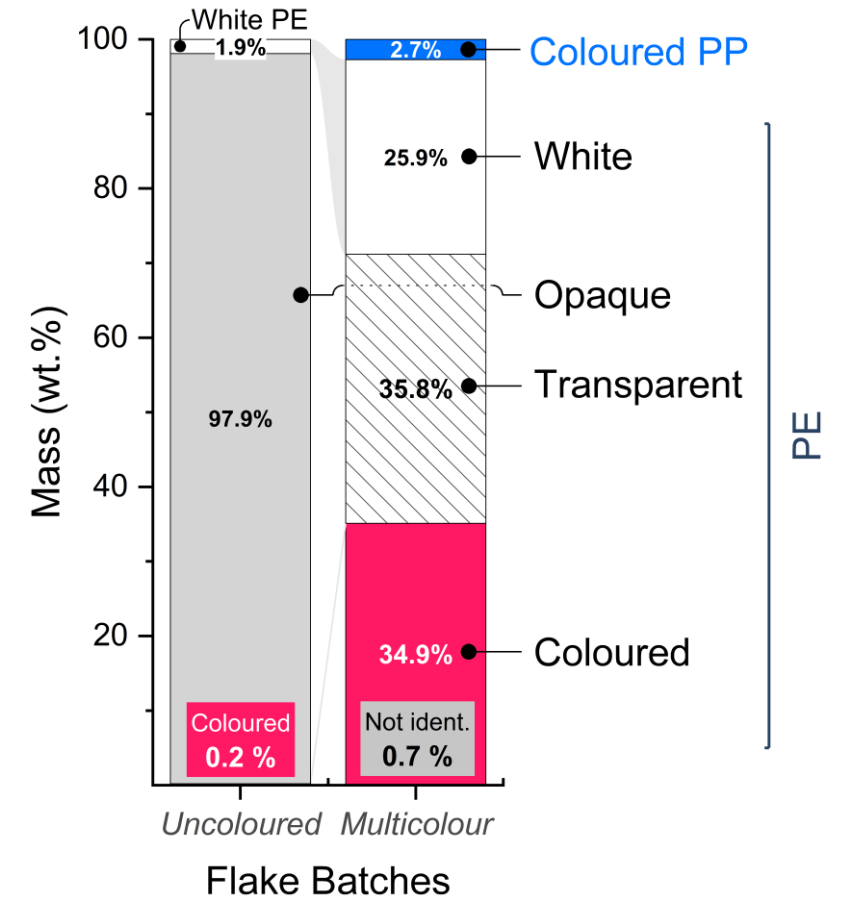
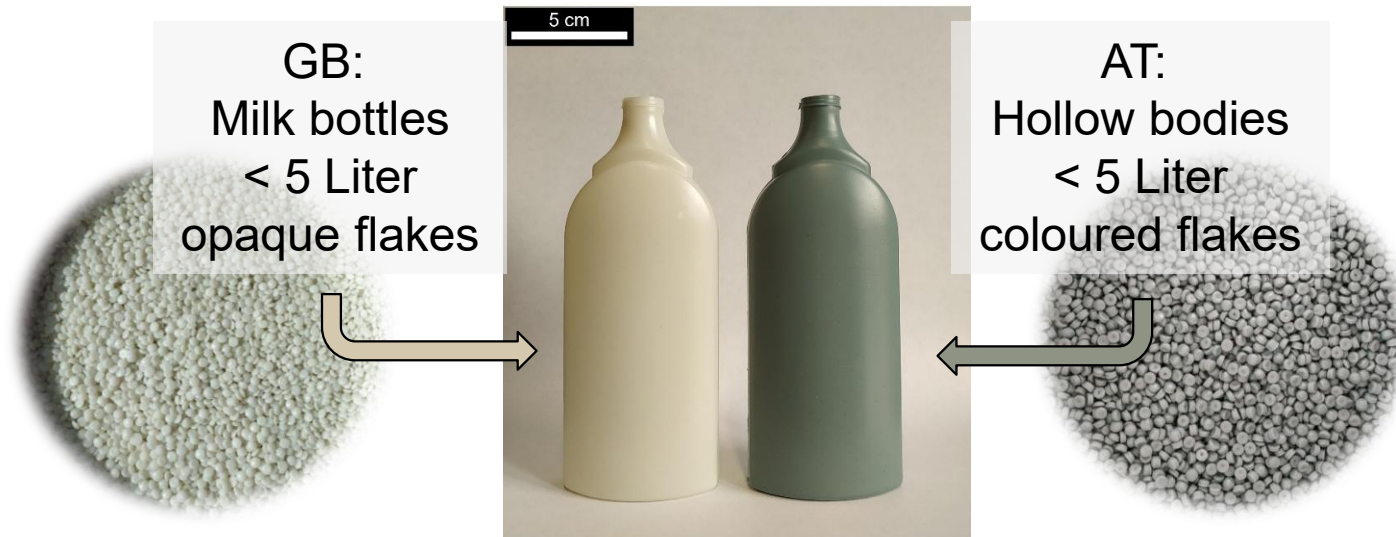
In order to meet the high stress crack resistance requirements for certain applications (e.g. cleaning detergents) virgin material would need to be blended



a) Drop test; b) Bulging on a recycled bottle; c) The base of a new bottle, showing no change

Separate Collection of 100% rPE-HD

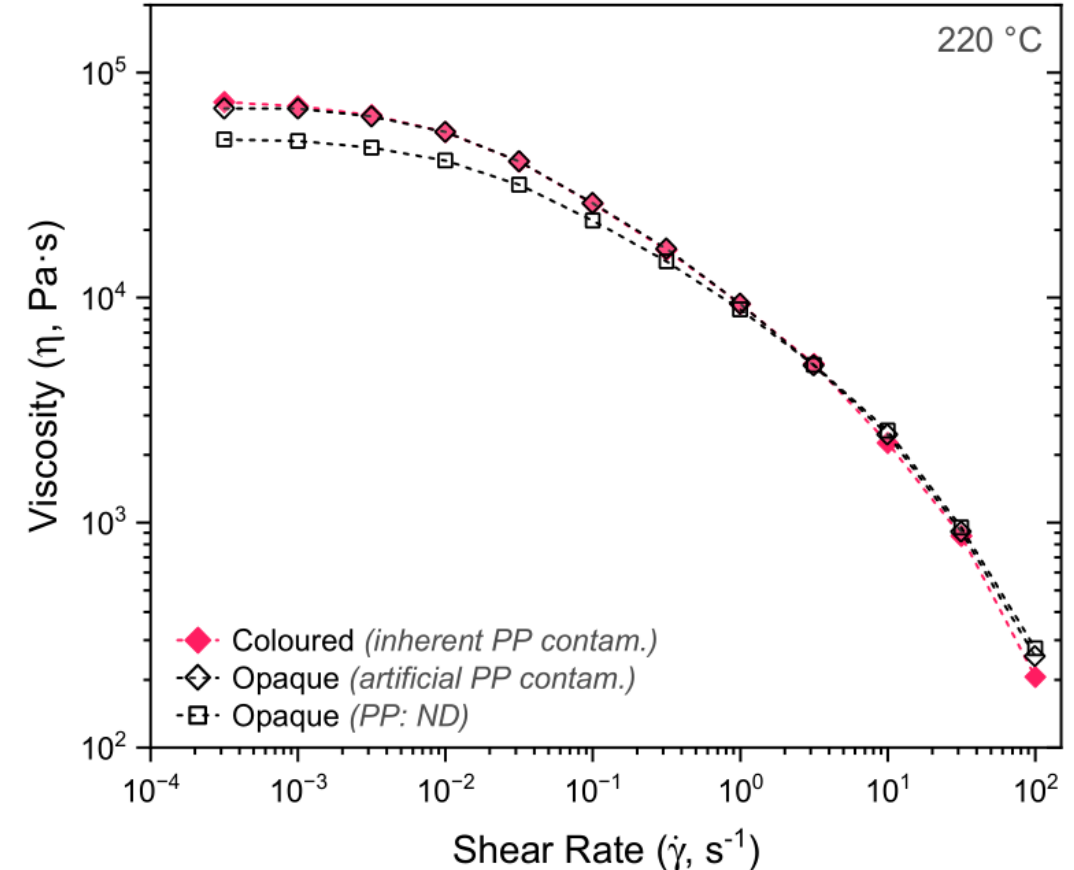
Comparison of two hollow-body fractions from hot-washed rPE-HD



Rheological properties 100% rPE-HD

■ Similarities

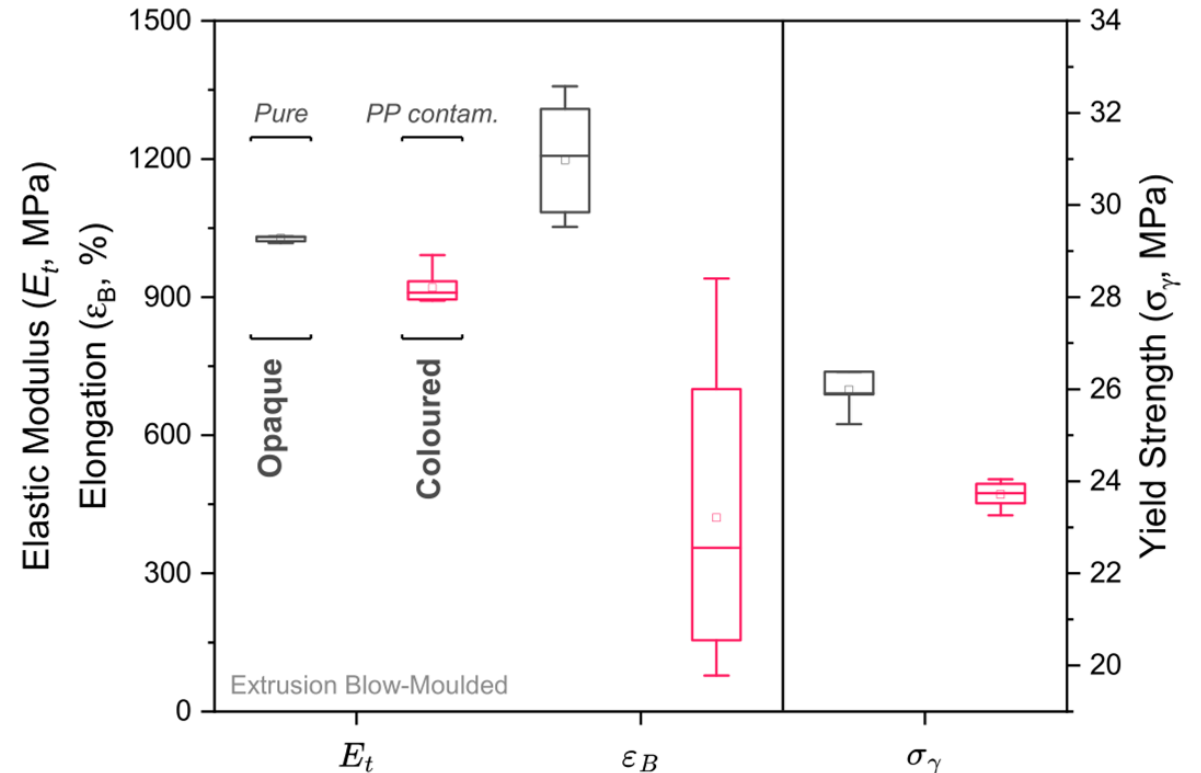
- Similar density of manufactured bottles (opaque: 0.944 ; multicoloured: $0.946 \text{ g}\cdot\text{cm}^{-3}$)
- Similar flow behaviour in the moderate shear rate range
- Creep behaviour in short-term testing (compressed specimens; room temperature, 24 h)
- Similar yield strength moduli (range: 4–5 MPa)



Mechanical properties 100% rPE-HD

- **Differences between the opaque (O) and multicoloured (MC) fractions**
- **MC:** less susceptible to thermal stress in the rheological time sweep (air, 220 °C, 14 minutes compared to 31.5 minutes until a 10% increase in complex viscosity)
- **O:** *Samples punched from bottles exhibit a noticeably higher and less variable elongation at break*

Tensile test: specimens punched from bottles



Challenges in washing

- **Removal of remaining decorative elements**
 - Resistance of adhesives and printing ink binders under standard washing conditions (H_2O ; NaOH_{aq})
 - Selection of suitable parameters for washing processes (e.g.: Temperature, Chemicals) to improve the quality of recyclates

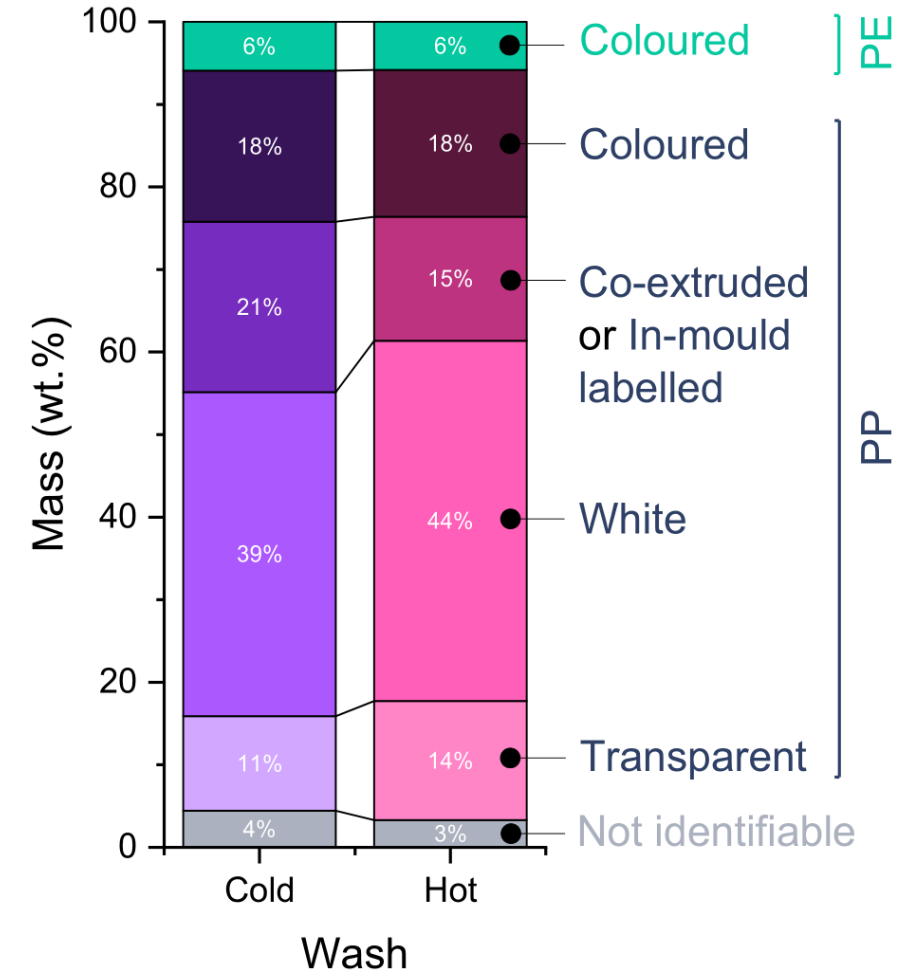
- **Removal of unwanted odours**
 - Requirement for melt degassing and additional treatment of the pellets to reduce volatile compounds

Key question:

Can washing and the removal of volatile substances increase the scope of application for PP recyclates?
Analysis of a fraction following **cold or hot** washing treatment

- Substance profile analysis using GC-MS (external)
- Monitoring of degradation behaviour using shear rheology and tensile testing

Composition of investigated rPP flake samples



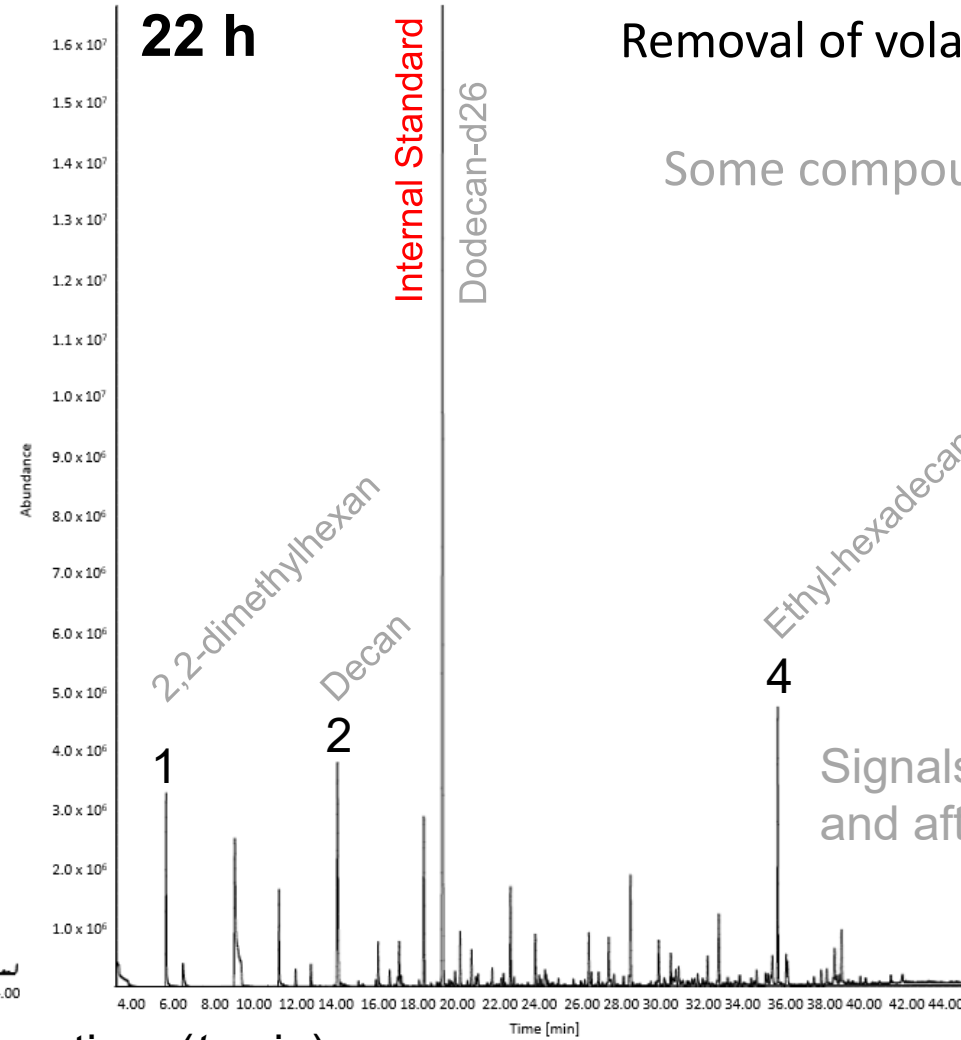
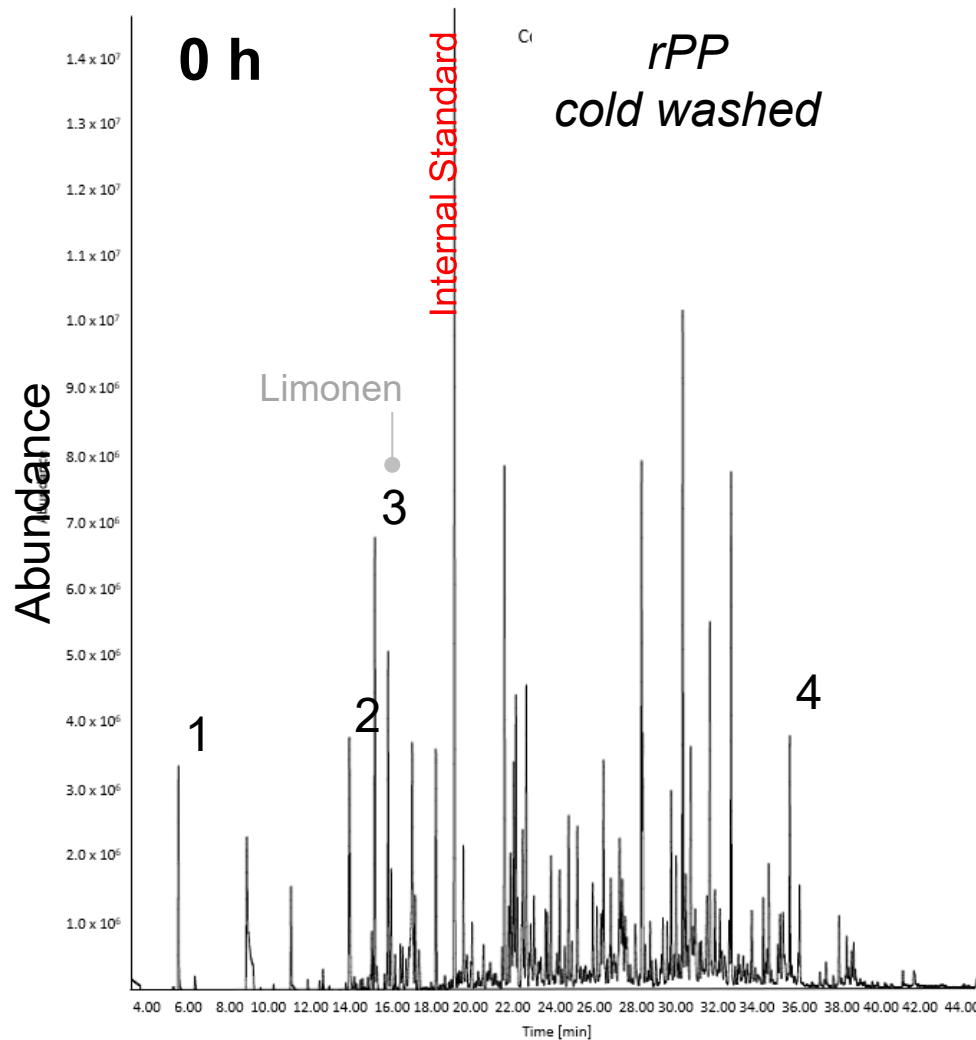
L. P. BICHLER, E. PINTER, T.; M.P. JONES, T. KOCH V.-M. ARCHODOULAKI. IMPACTS OF WASHING AND DEODORIZATION TREATMENT ON PACKAGING-SOURCED POST-CONSUMER POLYPROPYLENE. J MATER CYCLES WASTE MANAG 26, 3824–3837, 2024. [HTTPS://DOI.ORG/10.1007/S10163-024-02085-4](https://doi.org/10.1007/S10163-024-02085-4)

Washing rPP

Results of the GC-MS analysis:

Removal of volatile substances is largely effective

Some compounds remain due to their high boiling points



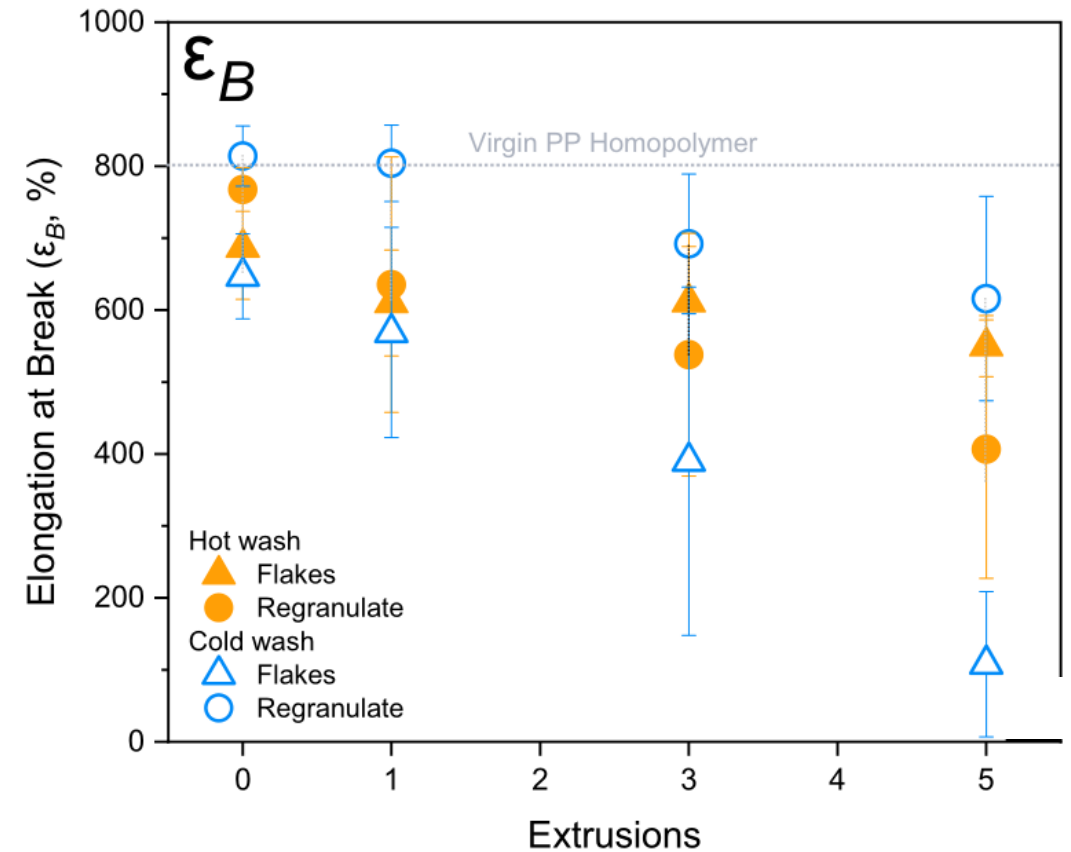
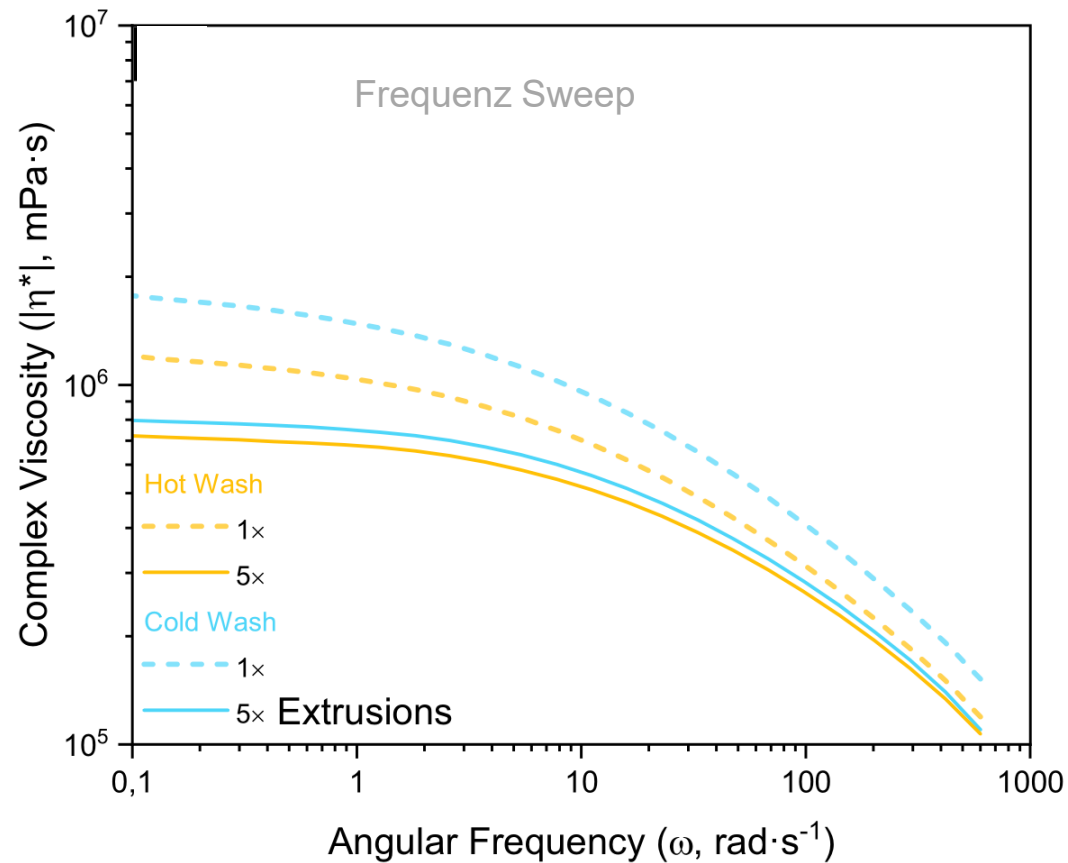
Signals bevor (0 h)
and after (22 h) hot air treatment

L. P. BICHLER, E. PINTER, T.; M.P. JONES, T. KOCH
V.-M. ARCHODOULAKI. IMPACTS OF WASHING AND
DEODORIZATION TREATMENT ON PACKAGING-
SOURCED POST-CONSUMER
POLYPROPYLENE. J MATER CYCLES WASTE
MANAG 26, 3824–3837, 2024.
[HTTPS://DOI.ORG/10.1007/S10163-024-02085-4](https://doi.org/10.1007/S10163-024-02085-4)

Chromatograms: E. Pinter, Ofi

Retentiontime (t , min)

Degradation behaviour resulting from repeated extrusion – a noticeable decrease in $|\eta^*|$ and ϵ_B



L. P. BICHLER, E. PINTER, T.; M.P. JONES, T. KOCH V.-M. ARCHODOULAKI. IMPACTS OF WASHING AND DEODORIZATION TREATMENT ON PACKAGING-SOURCED POST-CONSUMER POLYPROPYLENE. J MATER CYCLES WASTE MANAG 26, 3824–3837, 2024. [HTTPS://DOI.ORG/10.1007/S10163-024-02085-4](https://doi.org/10.1007/S10163-024-02085-4)

Quick Debrief

■ rPE-HD

- The recycling of PE-HD hollow bodies shows potential for further studies into commercial use

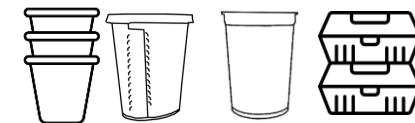
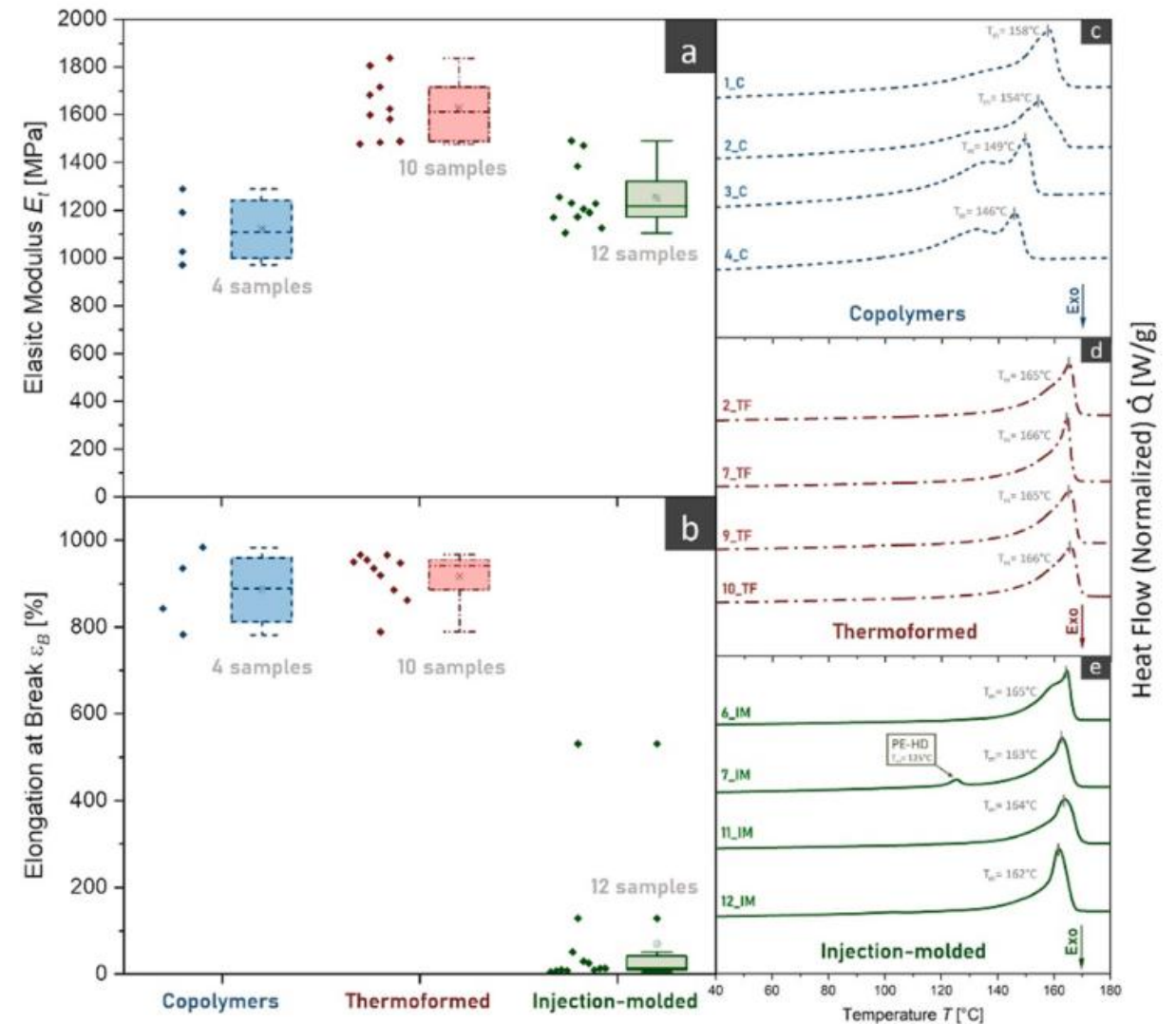
■ rPP

- Recyclates are currently still unsuitable for contact-sensitive packaging. To ensure comparability, further research is required regarding the direct comparison of fractions and washing processes

For food applications, standardising containers (and separate collection) can contribute to targeted sorting and thus enable largely homogeneous fractions

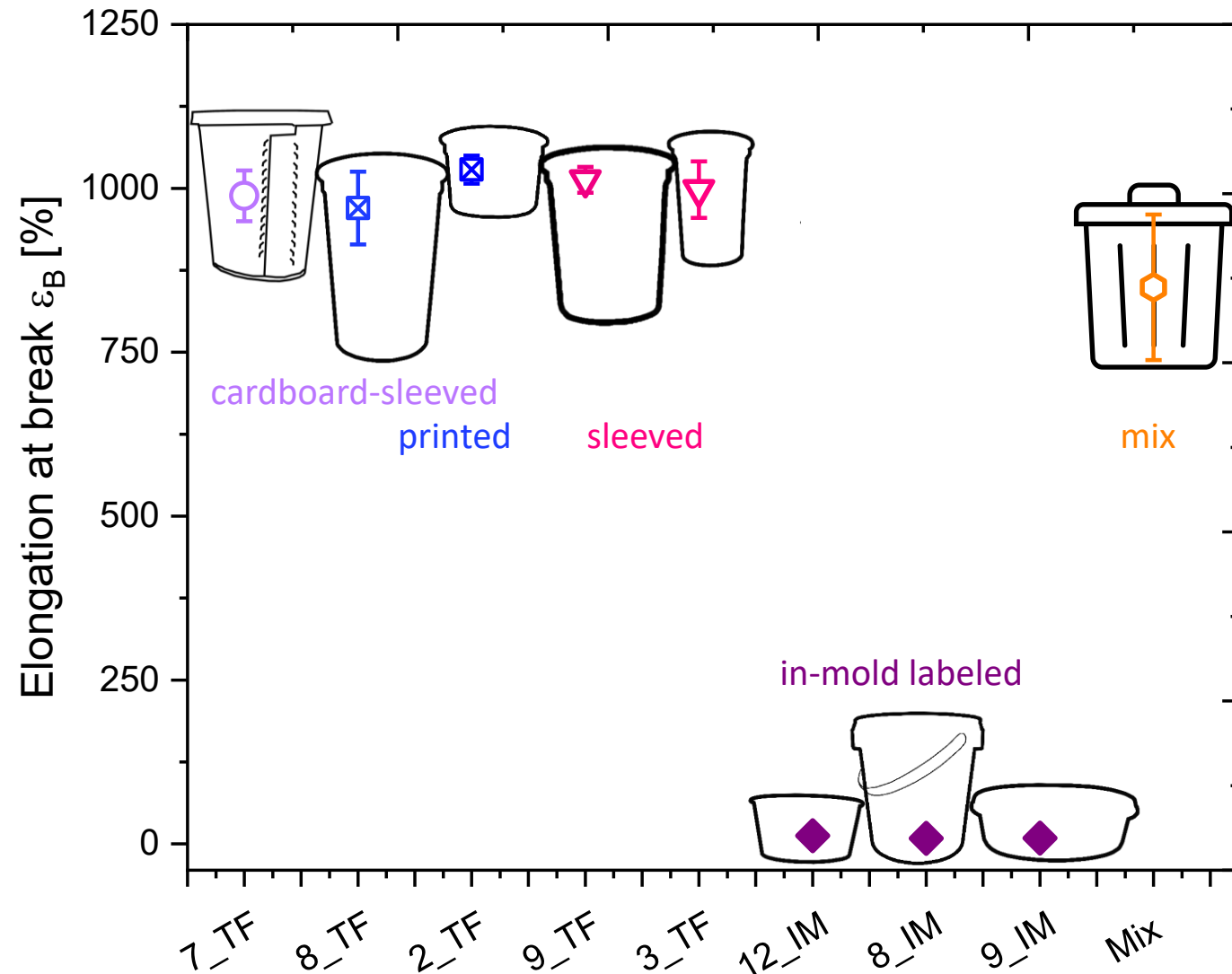
Analysis of post-consumer cups

- PP is very versatile
(Copolymers and Homopolymers)
- Cups
 - Thermoformed
 - Injection-moulded
- Offers a striking contrast in terms of elongation at break
- In Recycling → a combination of all these packaging types



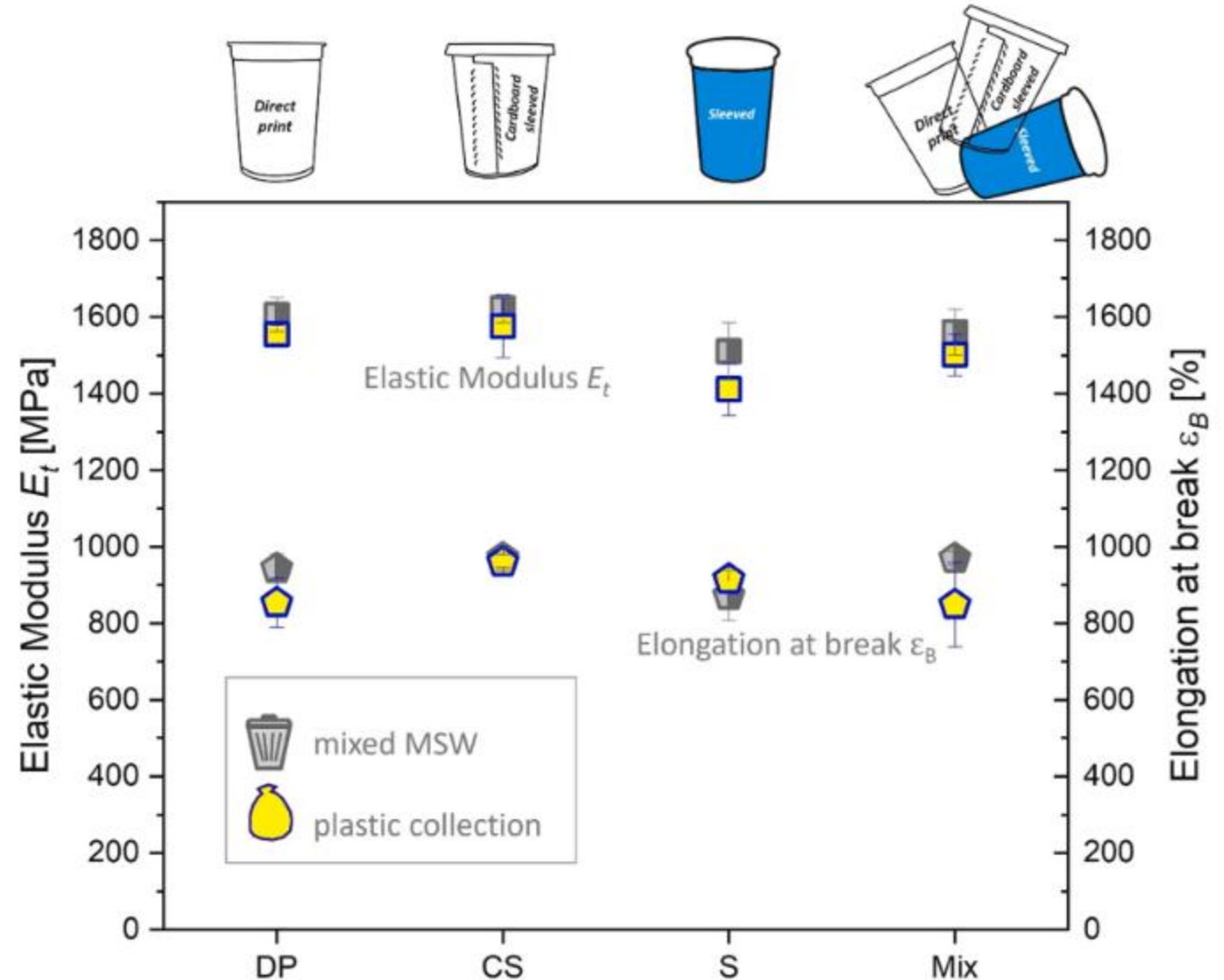
Polypropylene (yogurt) cups

- PP packaging is diverse
- Different properties
 - Especially elongation at break shows those differences
- In a recycling stream those properties are going to be combined
 - Next to different designs, labels, stabilizers & additives



Analysis of post-consumer (yogurt) cups

- Diversity of packaging designs
Size, material, design
- No differences due to
decoration
- collection (mixed MSW and
lightweight packaging)
- Processing from a residual waste
stream would be possible



Analysis of post-consumer (yogurt) cups

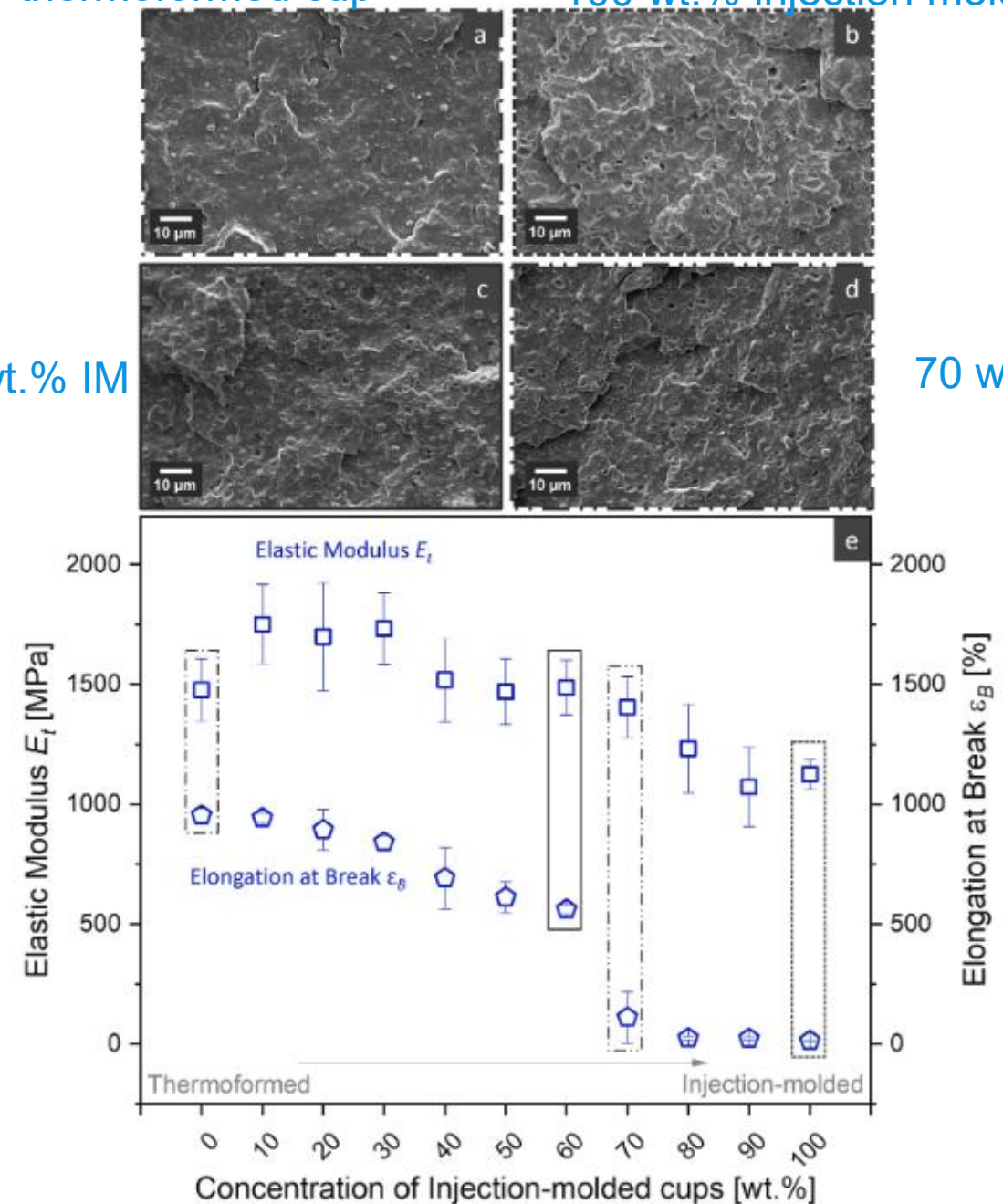
100 wt.% thermoformed cup
0% IM

100 wt.% injection molded cup

60 wt.% IM

70 wt.% IM

- Compounds containing up to 30% m.-% of the injection-moulded cup show properties similar to those of thermoformed cups
- REM (a-d):
 - thermoformed – ductile
 - Injection moulded – brittle



The influence of input stream

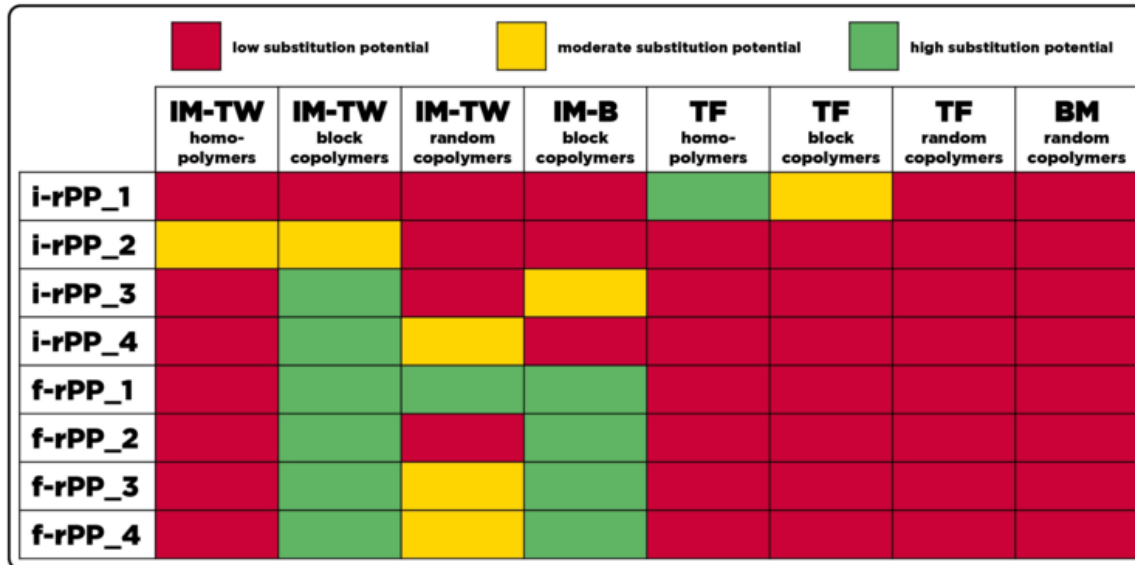


Figure 4. Substitution potential of investigated PP recyclates.

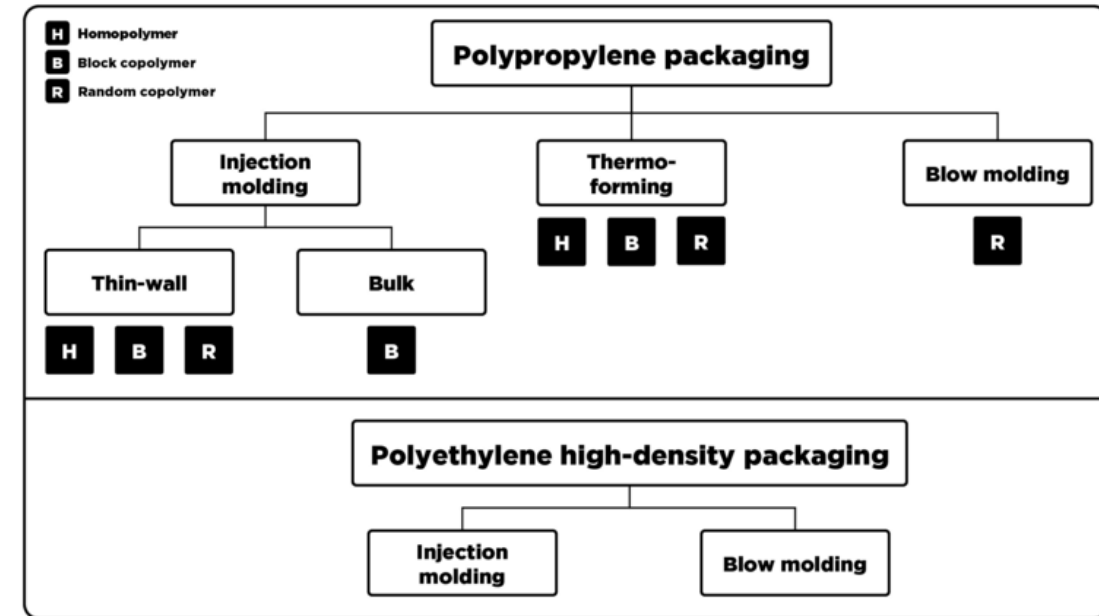


Figure 5. Substitution potential of investigated PE recyclates.

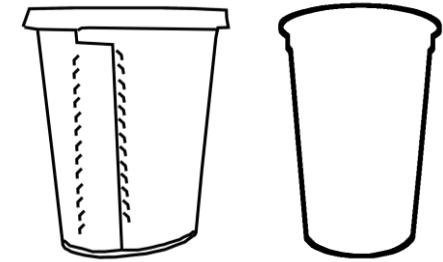
M. MAGER, M. BERGHOFER, J. FISCHER. POLYOLEFIN RECYCLATES FOR RIGID PACKAGING APPLICATIONS: THE INFLUENCE OF INPUT STREAM COMPOSITION ON RECYCLATE QUALITY. POLYMERS 2023, 15, 2776. [HTTPS://DOI.ORG/10.3390/POLYM15132776](https://doi.org/10.3390/POLYM15132776)



Key Objective: Preventing Contamination

- Sleeves or Cardboard Wrappers: Advantage for Pure PP Recyclate
 - **Detachable solutions:** The use of self-detaching sleeves is required to ensure clean separation during the washing and recycling phase
 - Blending Tolerances for IM & TF

Homogeneous Material Stream → Higher Recycling Quality



How do consumers perceive materials?

■ Plastic is convenient

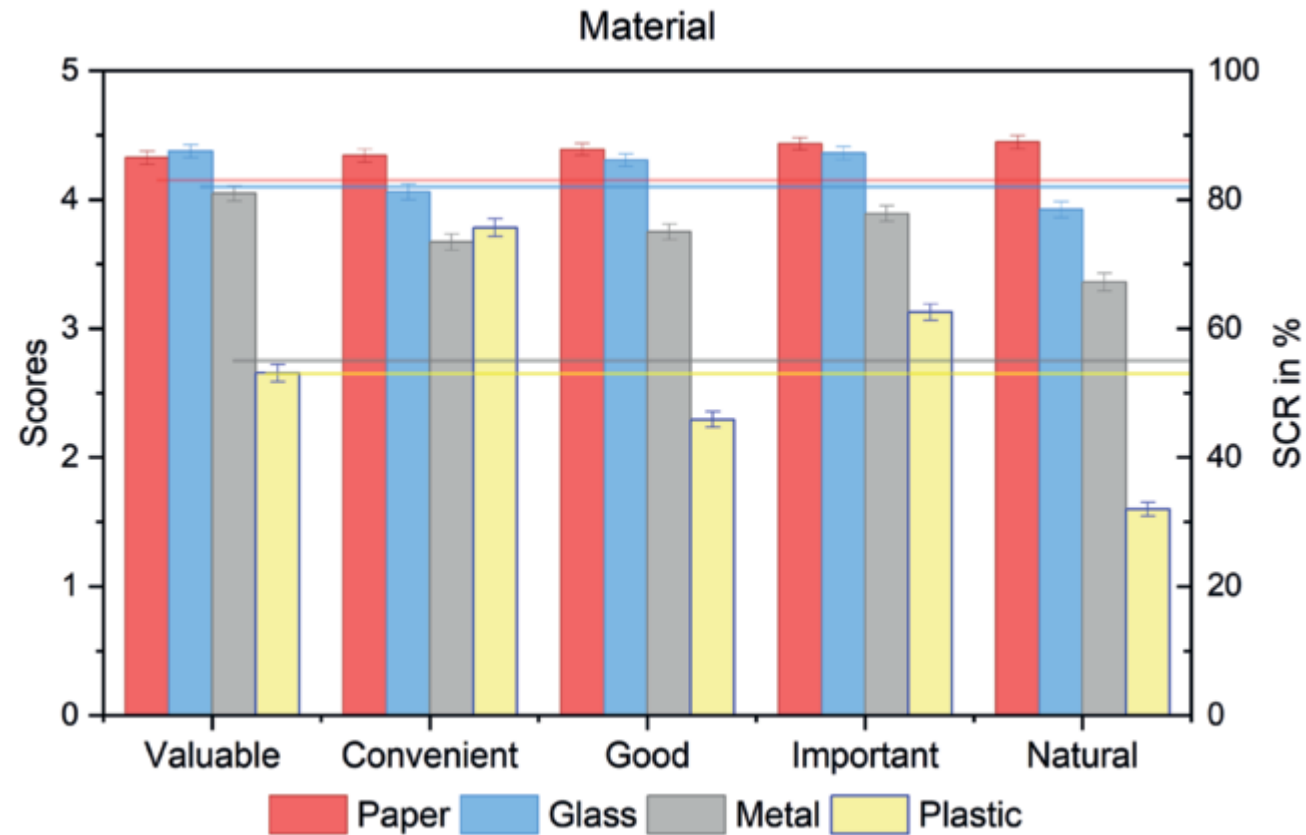
Rating scale from 1 to 5

worthless ① ● ● ● ● ⑤ valuable

■ Otherwise perceived as significantly less desirable

■ Higher-quality packaging is more likely to be recycled^[1,2]

■ Plastic has been promoted as a disposable product^[3]



Mean and standard errors of the perception of the different materials (paper, glass, metal, and plastic) in the dimensions valuable, convenient, good, important, and natural (N = 316). The respective Austrian separate collection rate (SCR) is displayed for information purposes as a line (right axis) containing the same colors and starting at the bar regarding the material.

J. SCHLOSSNIKL, B. HARTL, A.M. LIPP, J. LEDERER, V.-M. ARCHODOULAKI, HOW CONSUMERS PERCEIVE DIFFERENT MATERIALS, PACKAGING, AND WASTE: A PLASTIC-FOCUSED ANALYSIS, DETRITUS / VOLUME 35 - JUNE 2026 / PAGES 3-15, [HTTPS://DOI.ORG/10.31025/2611-4135/2026.19591](https://doi.org/10.31025/2611-4135/2026.19591)

[1] J. Langley, N. Turner, and A. Yoxall, "Attributes of packaging and influences on waste," Packaging Technology and Science, vol. 24, no. 3, pp. 161–175, Apr. 2011, doi: 10.1002/pts.924.

[2] B. Nemat, M. Razzaghi, K. Bolton, and K. Roustae, "Design affordance of plastic food packaging for consumer sorting behavior," Resour Conserv Recycl, vol. 177, p. 105949, Feb. 2022, doi: 10.1016/j.resconrec.2021.105949.

[3] J. L. Meikle, American plastic: a cultural history. Rutgers University Press, 1995.

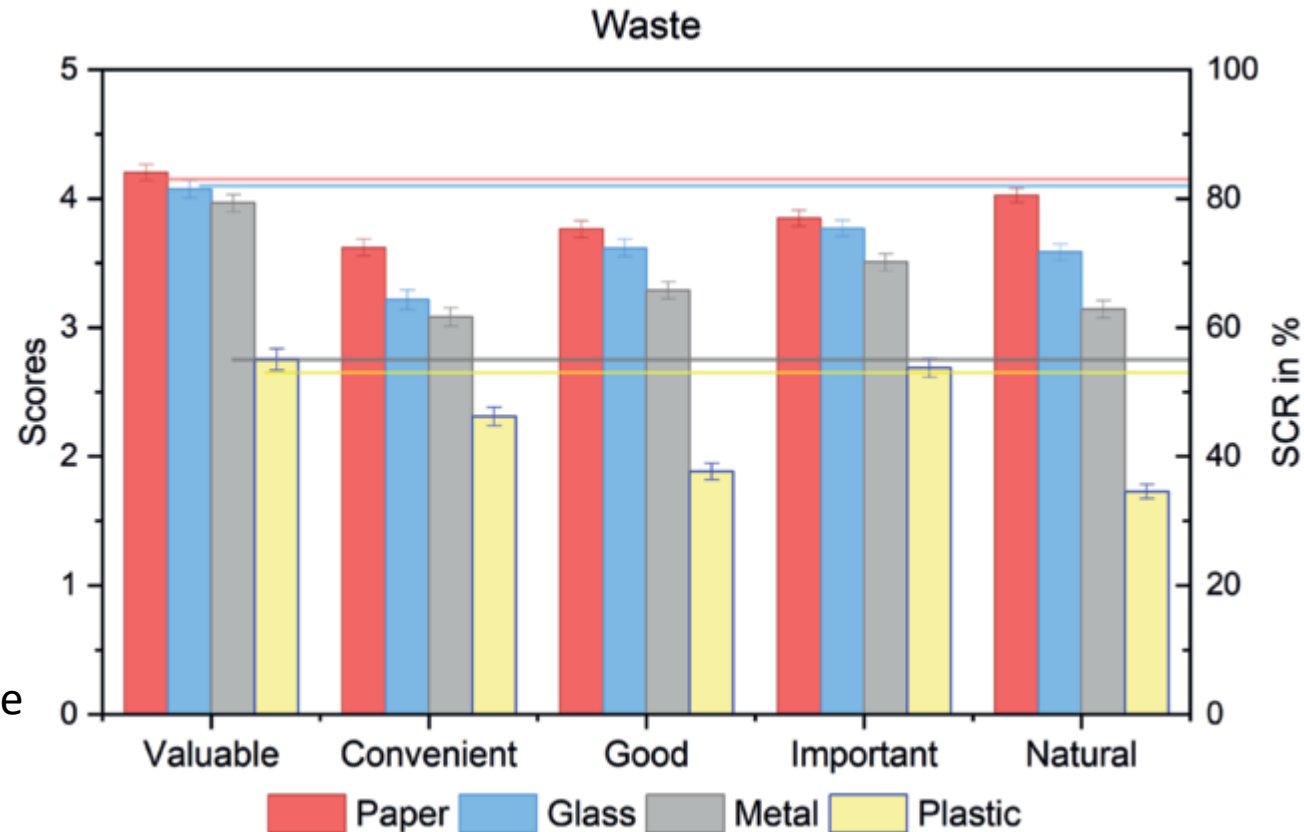
How do consumers perceive materials as waste?

Mean and standard errors for the perception of the disposed of material (paper, glass, metal, and plastic) in the dimensions valuable, convenient, good, important, and natural (N = 316). The respective Austrian separate collection rate **SCR***^[2] is displayed as a line (right axis) containing the same colors and starting at the bar regarding the material.

Even as waste, the other materials are still perceived positively!

Pckaging material	Recycling-rate 2021 % ^[1]
Papier	81
Glas	82
Metall	74
Plastik	26

* In the case of plastic packaging, the difference is due to sorting losses in sorting plants, resulting in lower recycling rates than SCRs.



J. SCHLOSSNIKL, B. HARTL, A.M. LIPP, J. LEDERER, V.-M. ARCHODOULAKI, HOW CONSUMERS PERCEIVE DIFFERENT MATERIALS, PACKAGING, AND WASTE: A PLASTIC-FOCUSED ANALYSIS, DETRITUS / VOLUME 35 - JUNE 2026 / PAGES 3-15, [HTTPS://DOI.ORG/10.31025/2611-4135/2026.19591](https://doi.org/10.31025/2611-4135/2026.19591)

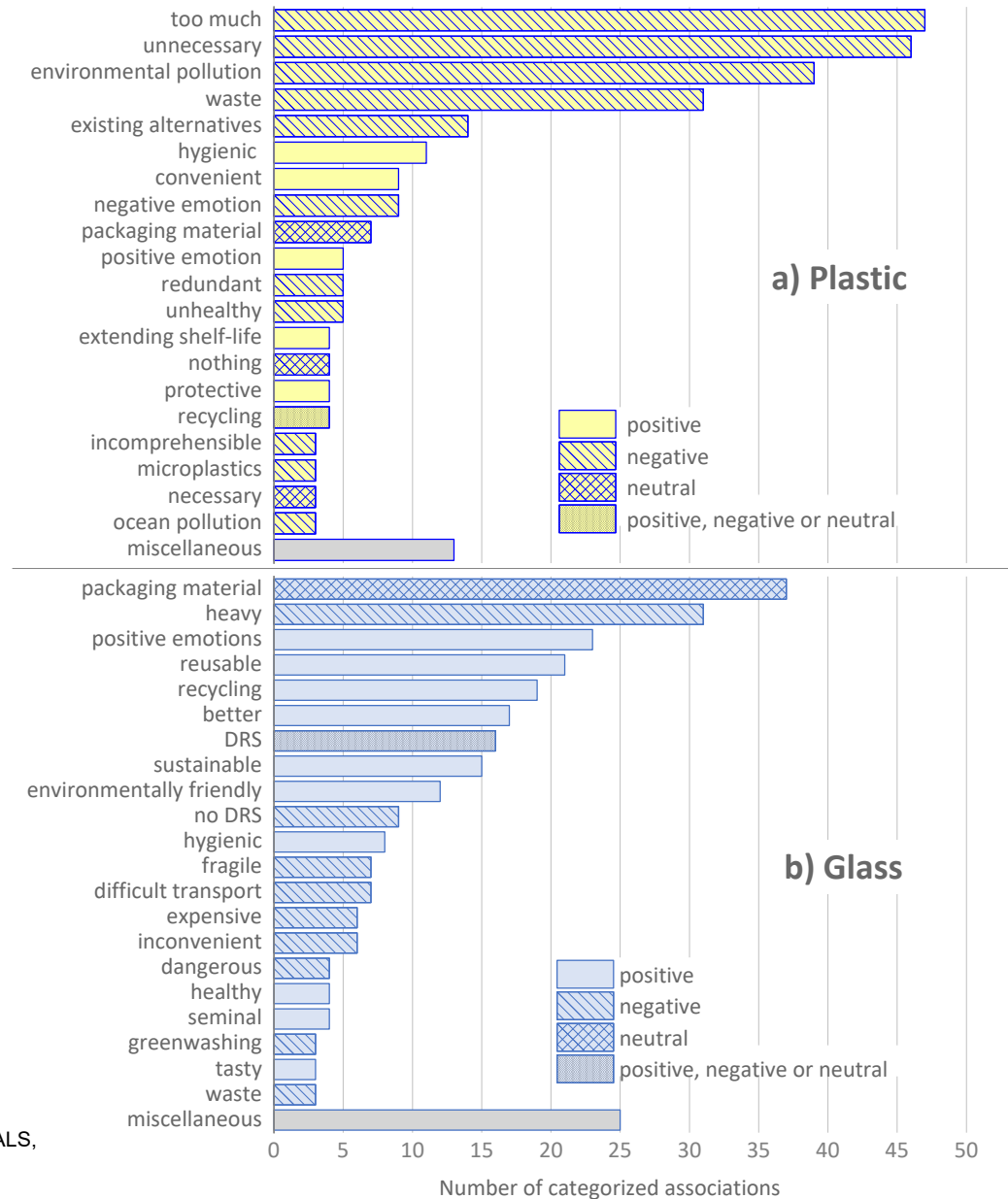
[1] BMK. (2024). DIE BESTANDSAUFNAHME DER ABFALLWIRTSCHAFT IN ÖSTERREICH, STATUSBERICHT 2024.

[HTTPS://WWW.BMLUK.GV.AT/SERVICE/PUBLIKATIONEN/KLIMA-UND-UMWELT/DIE-BESTANDSAUFNAHME-DER-ABFALLWIRTSCHAFT-IN-OESTERREICH-STATUSBERICHT-2024-FUER-DAS-REFERENZJAHR-2022.HTML](https://www.bmluk.gv.at/service/publikationen/klima-und-umwelt/die-bestandsaufnahme-der-abfallwirtschaft-in-oesterreich-statusbericht-2024-fuer-das-referenzjahr-2022.html)

[2] A.-M. LIPP, J. LEDERER, THE CIRCULAR ECONOMY OF PACKAGING WASTE IN AUSTRIA: AN EVALUATION BASED ON STATISTICAL ENTROPY AND MATERIAL, FLOW ANALYSIS., RESOURCES, CONSERVATION AND RECYCLING, 217, 2025, 108193, [HTTPS://DOI.ORG/10.1016/J.RESCONREC.2025.108193](https://doi.org/10.1016/j.resconrec.2025.108193).

Free Associations

- Plastic: "too much", "unnecessary" and "environmental pollution"
- Glass: "packaging material", "heavy" then very positive
- 80% of the categorized associations of plastic are negative and 30% of glass



Consumer perspective

- The negative Image of plastic is deeply rooted
- Perception of plastic is poorer than that of any other material
 - as product
 - as waste



Consumers represent an indispensable factor for the circular economy ^[1]



Symbols and clear messaging are required ^[1] → **plastic is valuable**

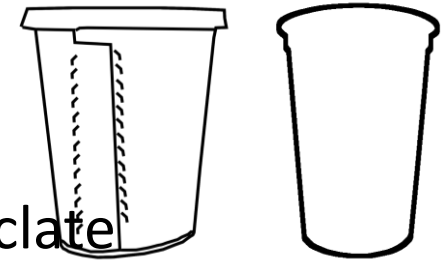


Standardized labeling from collection through to the finished product

J. SCHLOSSNIKL, B. HARTL, A.M. LIPP, J. LEDERER, V.-M. ARCHODOULAKI, HOW CONSUMERS PERCEIVE DIFFERENT MATERIALS, PACKAGING, AND WASTE: A PLASTIC-FOCUSED ANALYSIS, DETRITUS / VOLUME 35 - JUNE 2026 / PAGES 3-15, [HTTPS://DOI.ORG/10.31025/2611-4135/2026.19591](https://doi.org/10.31025/2611-4135/2026.19591)

[1] J. KIRCHHERR, D. REIKE, AND M. HEKKERT, "CONCEPTUALIZING THE CIRCULAR ECONOMY: AN ANALYSIS OF 114 DEFINITIONS," RESOUR CONSERV RECYCL, VOL. 127, PP. 221-232, 2017, DOI: 10.1016/J.RESCONREC.2017.09.005.

[2] N. D. STEENIS, E. VAN HERPEN, I. A. VAN DER LANS, T. N. LIGTHART, AND H. C. M. VAN TRIJP, "CONSUMER RESPONSE TO PACKAGING DESIGN: THE ROLE OF PACKAGING MATERIALS AND GRAPHICS IN SUSTAINABILITY PERCEPTIONS AND PRODUCT EVALUATIONS," J CLEAN PROD, VOL. 162, PP. 286-298, 2017, DOI: 10.1016/J.JCLEPRO.2017.06.036



Key Objective: Preventing Contamination



- Sleeves or Cardboard Wrappers: Advantage for Pure PP Recyclate
 - **Detachable solutions:** The use of self-detaching sleeves is required to ensure clean separation during the washing and recycling phase
 - Blending Tolerances for IM & TF

Homogeneous Material Stream → Higher Recycling Quality

J. SCHLOSSNIKL, L. GRITSCH, T. KOCH, V.-M. ARCHODOULAKI, DESIGN AND MANUFACTURING DIVERSITY UNDERMINE CIRCULARITY: THE CASE OF A SIMPLE YOGURT CUP, RESOURCES, CONSERVATION AND RECYCLING, VOLUME 212, 2025, 107944, [HTTPS://DOI.ORG/10.1016/J.RESCONREC.2024.107944](https://doi.org/10.1016/j.resconrec.2024.107944).

Special focus was put on three- component (3C) yoghurt cups (consisting of a plastic cup, an aluminum cover, and a carton wrap. Looking at the **dismantling stage** of separately collected cups, between 50-57% of 3C cups and 72-88% of yoghurt cups with other decoration types were completely separated from their subcomponents, enabling recycling of the plastic cup. **However, 95% of all yoghurt cups (by number) in Vienna were disposed of via mixed municipal solid waste and further incinerated, resulting in about 164 million yoghurt cups, primarily consisting of polypropylene, which are lost for mechanical recycling.**

G. BRESLMAYER, L. GRITSCH, J. LEDERER, A CASE STUDY OF PLASTIC YOGHURT CUP S IN VIENNA
GLOBAL CHALLENGES, 2026; 10:E70144 [HTTPS://DOI.ORG/10.1002/GCH2.70144](https://doi.org/10.1002/GCH2.70144)

The Critical Role of Sorting & Pretreatment

- **The Purity Requirement:** Precise sorting is the bottleneck of the recycling industry because subsequent processing technologies demand highly pure material fractions.
- **Fiber Separation:** Accurate separation of natural fibers from synthetic fibers is essential, as both groups require entirely different downstream recycling techniques.
- **The Blended Fabric Challenge:** Significant efficiency losses and separation issues arise when a garment consists of a complex mixture of different materials.
- **Sorting Methodology:** The industry utilizes a combination of manual sorting and automated methods to maximize overall recycling efficiency and minimize environmental impact (NIR, RFID, Bar Codes, TRL 8-9).
- **The Need for Traceability:** Improved traceability of the specific materials and chemical additives used in textiles is urgently needed to upgrade the efficiency of current sorting technologies.

I.E. LANZ, E. LABORDA, C. CHAINE, M.BLECUA. A MAPPING OF TEXTILE WASTE RECYCLING TECHNOLOGIES IN EUROPE AND SPAIN. TEXTILES, 2024, 4, 359–390.
[HTTPS://DOI.ORG/10.3390/TEXTILES4030022](https://doi.org/10.3390/textiles4030022)

Points for discussion

- Moving beyond the rigid "closed loop" dogma
- Design for Recycling and Design from Recycling are essential for any progress
- Yogurt cups are a prime example of how too much diversity can be counterproductive
- The status quo: Reducing weight is currently favored over improving recyclability
- The negative perception of plastic is deeply embedded, we have to change it

The "Honesty Box" Experiment



The Setup (Newcastle University)

- **Context:** An office coffee station relying on an honor system for payment.
- **The Variable:** The poster above the money box changed every week:
 - *Week A:* Images of **Flowers** 🌸
 - *Week B:* Images of **Eyes** 👁️



The Result

- **3x More Cash:** Payments tripled during the weeks with the "eyes" posters.
- **Zero Awareness:** Not a single participant consciously noticed the influence.



Kahneman's Key Takeaway (System 1)

- **Subconscious Trigger:** Evolutionary cues (eyes) instantly signal "you are being watched."
- **Automatic Honesty:** Behavior changes without any rational, conscious deliberation.

DANIEL KAHNEMAN, THINKING, FAST AND SLOW

Plastics sorting in South Korea is called "**Bunri Baechul**" (분리배출 - **Separate Discharge**)

- **Bin 1:** Transparent PET bottles only (Labels removed)
- **Bin 2:** Colored PET & General Plastics (PP, PE, PS, OTHER mixed together)
- **Bin 3:** Expanded Polystyrene
- **Bin 4:** Plastic Bags / Vinyl wrappers (Snack bags, grocery bags)

The government does not expect citizens to look at the tiny numbers (1 through 7)

to sort PP from PE. The consumer's strict responsibility focuses on **material condition**:

- **Empty and Rinse:** If a PP delivery container has red chili oil stains that cannot be washed out, it **cannot** go into the plastic recycling. The consumer must throw it in the general burnable waste bag (*Jongnyangje*).
- **Strip Labels:** All vinyl stickers and labels must be peeled off and put into the vinyl recycling stream.



Challenges and Opportunities

Challenges

Sorting Limitations: Automated systems struggle with multi-layer films, dark-colored polymers, and closely related resin types, leading to cross-contamination.

Washing & Decontamination: Removing organic residues, odors, and toxins requires high water and energy consumption. Food-contact safety standards are difficult to meet.

Material Degradation: Repeated mechanical recycling shortens polymer chains, reducing quality.

Opportunities

Tech Innovation: AI-driven sorting, digital watermarks, and advanced washing

Policy Drivers: Strict EU mandates (like PPWR) enforce eco-design and mandatory recycled content.

Consumer Action: Consumer awareness and behavior impact the demand for recycled products.

Education campaigns and incentives can stimulate demand. Deposit-return schemes and information improve collection rates and reduce contamination.

„Recycling is just the aspirin for the collective hangover of our consumption addiction“

source: unknown

Thank you for your attention!

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