Plastics Recycling – Status quo and Outlook

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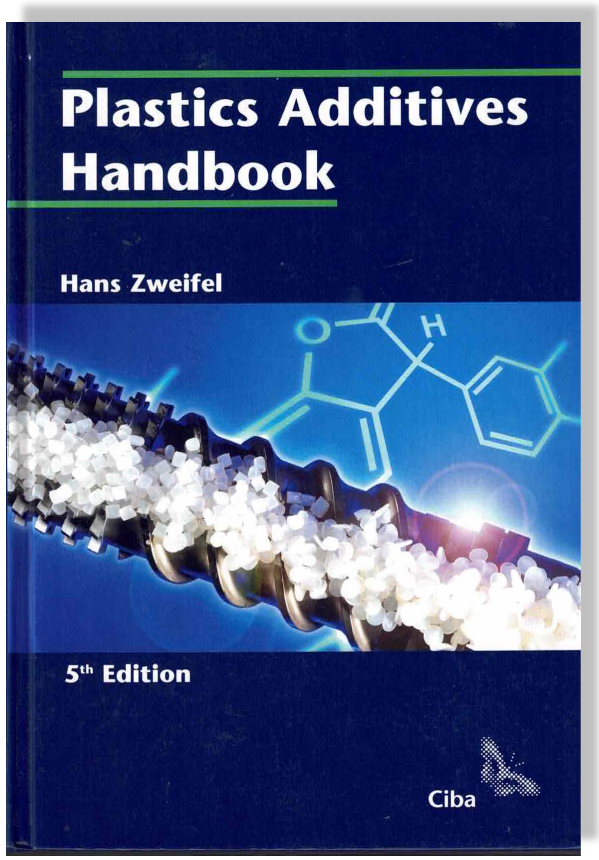
Key Questions

- Is the vision of the 1970s of being able to make new products from (mixed, post-consumer = PC) plastic waste still realistic today?
- What else do we recycle besides polymers?
- How many cycles does (PC) plastic recycling achieve?
- How does high-quality recycling work?

https://www.sesotec.com/emea/fr/resources/food-safety-ueberblick-2

The Variety

- Plastics are a mixture of polymers with an average of a few to over 50 % by weight of additives.
- Manuals provide a good overview of which additive groups are used for what:
  - Plasticizers, flame retardants, stabilizers, antioxidants, acid scavengers, lubricants, dyes/pigments, optical brighteners, surface treatment agents, coating agents, biocides, emulsifiers, release agents, blowing agents, processing aids, antifogging agents, antistatic agents, extenders, reinforcing agents, fragrances.
  - There are also NIAS (Non Intentionally Added Substances).
- Each of these groups is represented by just under ten to over 100 individual substances.
- In total, the common additives comprise over 1,000 individual substances.



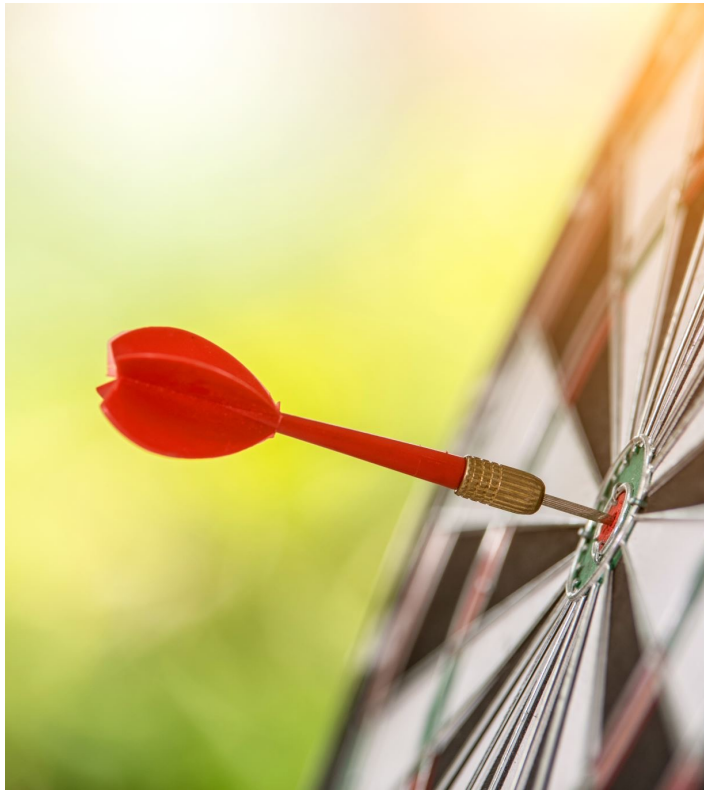
The Variety II

In today's plastic products, the polymer molecule is generally no longer uniform; so-called homopolymers are on the decline.

- Polymers made of different monomers (so-called hetero- or co-polymers) are widespread.
- Covalent compounds between different polymers are on the increase (cross-linking).
- Mixtures of several polymers (so-called blends) are increasingly being used.
- Composites of plastics with plastics or other materials are also frequently encountered.
- Fibers/fabrics are also being incorporated.

Interim Conclusion I

- As expected, this current diversity is particularly high in mixed post-consumer (PC) plastic waste (packaging, technical equipments, cars, constructions, etc.).
- PC recyclates are a reflection of this diversity.
- **New high-quality products are optimized for the respective application through polymer compositions and additive formulations.**
- PC recyclates can generally no longer be integrated at this high level (this does not apply to closed loop and production residue recycling).
- We are therefore observing downcycling.



Circularity

Plastics are usually recycled by re-melting of the waste plastics.

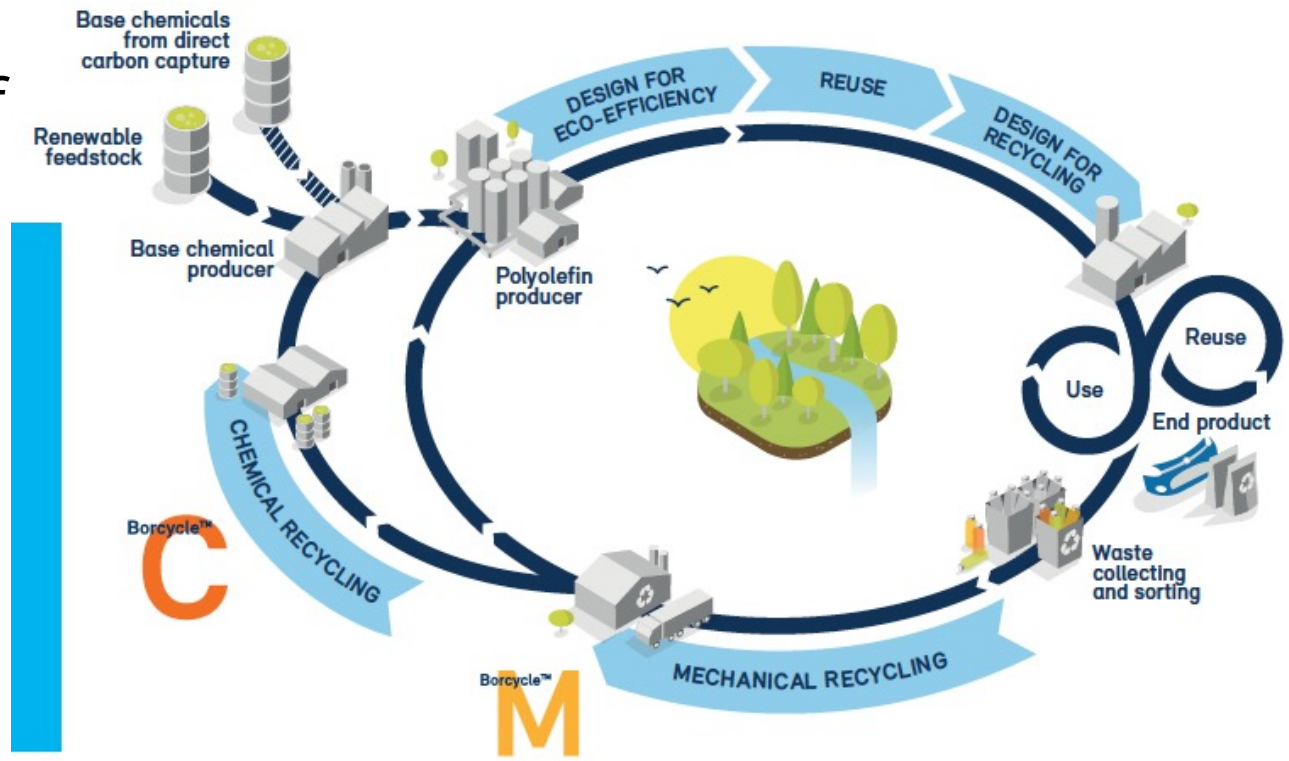
- This damages some polymer molecules (chain shortening, oxidation, etc.).
- This increases the migration of additives from products.
- New contaminants are formed (Non Intentionally Added Substances, NIAS → Backup).
- Impurities lead to material defects.
- The defects increase with each cycle.
- Recyclates from packaging waste often have unpleasant odors.
- There are serious marketing problems.

https://commons.wikimedia.org/wiki/File:Downcycling_symbol.svg#/media/File:Downcycling_symbol.svg

Interim Conclusion II

- Strictly speaking, the closed-loop concept requires infinite cycles of materials.
- Material recycling of glass or metals achieves this.
- Material recycling of mixed PC waste plastics only creates very few cycles – if any at all.
- Downcycling contradicts the closed-loop concept.

Example Borealis



https://www.borealisgroup.com/storage/Polyolefins/Circular-Economy-Solutions/Borcycle/Borcycle-C-The-solution-for-high-purity-high-performance-recycled-materials.pdf

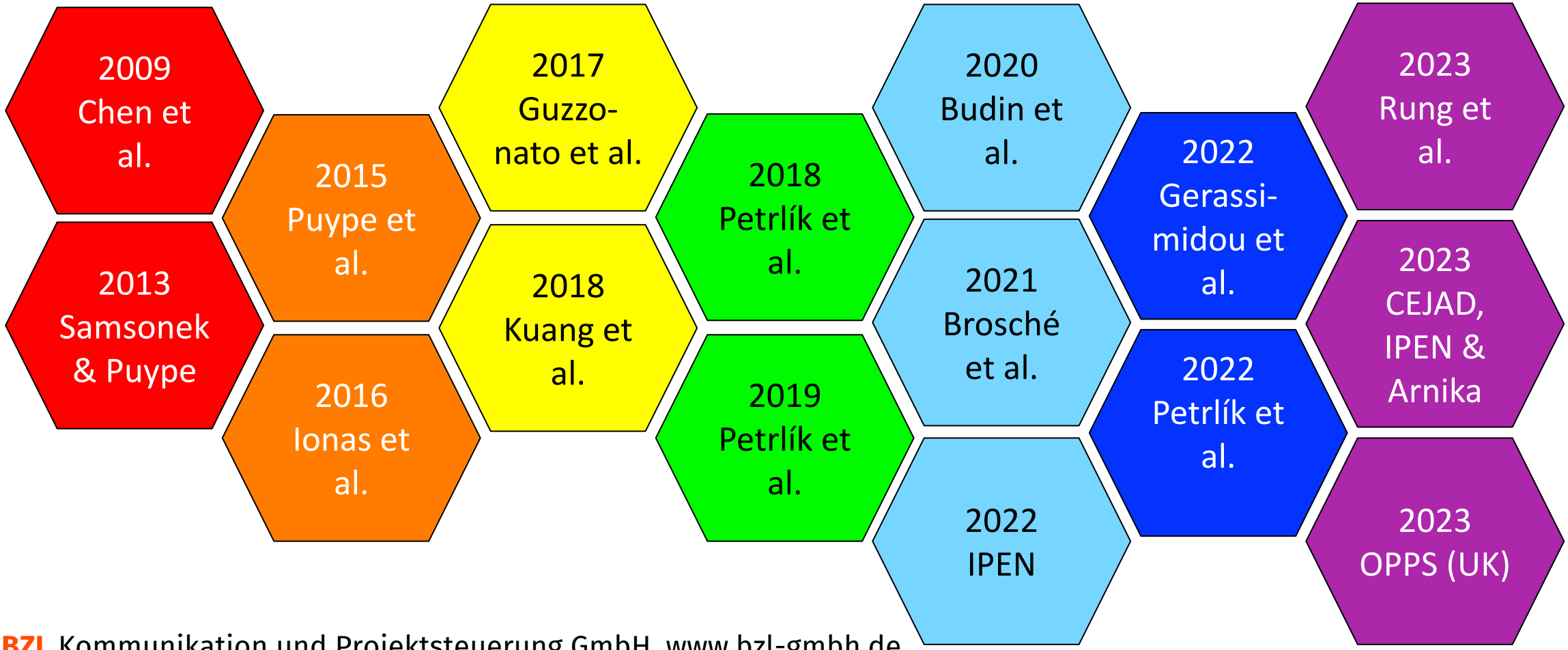
Prohibited Additives

Many additives that have been used legally in the past are now banned, such as certain **POPs** or **SVHCs**. A selection:

Function	Substance group	Representatives	Effect/Risk
Plasticizer	Phthalates	DEHP, DBP, BBP, DIBP	Hormonal effect → Reproductive hazard
Flame retardant	Halogen compounds	Polybrominated und Polychlorinated substances, Chlorinated paraffins (CP)	Carcinogenic, bioaccumulative, developmental neurotoxic effects
Stabilizers	Heavy metals	Cadmium, lead, tin	Kidney toxicant, carcinogenic
Pigments/dyes	Organic pigment	Carbon Black, Azo-compounds (aromatic amines)	Potentially carcinogenic
Surface treatment	Perfluorinated organic substances, PFAS	Perfluorooctane sulfonate (PFOS) Perfluorooctanoic acid (PFOA)	Persistent, bioaccumulative, harmful to health, possibly carcinogenic

Risk Cycle

Risk cycle = banned additives end up in new products via recyclates! The list of studies on this is long. Here is a selection (more → Backup):



Packaging not affected?

Is packaging for the food sector (FCM, Food Contact Materials) less problematic for recycling, also because, unlike technical plastics, it does not come from the "dark" past?

https://www.youtube.com/watch?v=JG1A6aAGOGc

- In a **recent** study (Zimmermann et al., 2022), 197 chemicals were identified that are intentionally used in plastic materials that come into contact with food and are considered hazardous according to the criteria of the EU Chemicals Strategy for Sustainability (**FCCoCs**, Food Contact Chemicals of Concern). Some of them are classified as carcinogenic, mutagenic or toxic to reproduction.
- And additives can be detected in food: A **recent** meta-study on FCM packaging evaluated 116 laboratory studies that measured the migration of additives into food. A total of 211 substances were found to have migrated from PE food packaging into food. Only 25% of these substances are approved for the FCM sector in the EU (Gerassimidou et al., 2022).

- Gerassimidou, S.; Lanska, P.; Hahladakis, J.; Lovat, E.; Vanzetto, S.; Geueke, B.; Groh, K. S.; Muncke, J.; Maffini, M.; Martin, O. V.; Iacovidou, E. (2022): Unpacking the Complexity of the PET Drink Bottles Value Chain: A Chemicals Perspective. Journal of Hazardous Materials 430: 128410. https://doi.org/10.1016/j.jhazmat.2022.128410
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Risk Cycle – "black sheep"

A **recent** study of consumer products and children's toys containing **black plastics** from all continents of the world has produced very worrying results (**Behnisch et al., 2023**).

More than 60% of the products analyzed had higher concentrations of dioxins than the provisional limit value for toxic waste contained in the Basel Convention (1 mg TEQ/t). The authors thus confirm their own older findings (Petrlík et al., 2019; Budin et al., 2020).

- Behnisch, P.; Petrlík, J.; Budin, C.; Besselink, H.; Felzel, E.; Strakova, J.; Bell, L.; Kuepouo, G.; Gharbi, S.; Bejarano, F.; Jensen, G. K.; DiGangi, J.; Ismawati, Y.; Speranskaya, O.; Da, M.; Pulkrabova, J.; Gramblicka, T.; Brabcova, K.; Brouwer, A. (2023): Global survey of dioxin- and thyroid hormone-like activities in consumer products and toys. Environment International 178 (2023) 108079 https://doi.org/10.1016/j.envint.2023.108079
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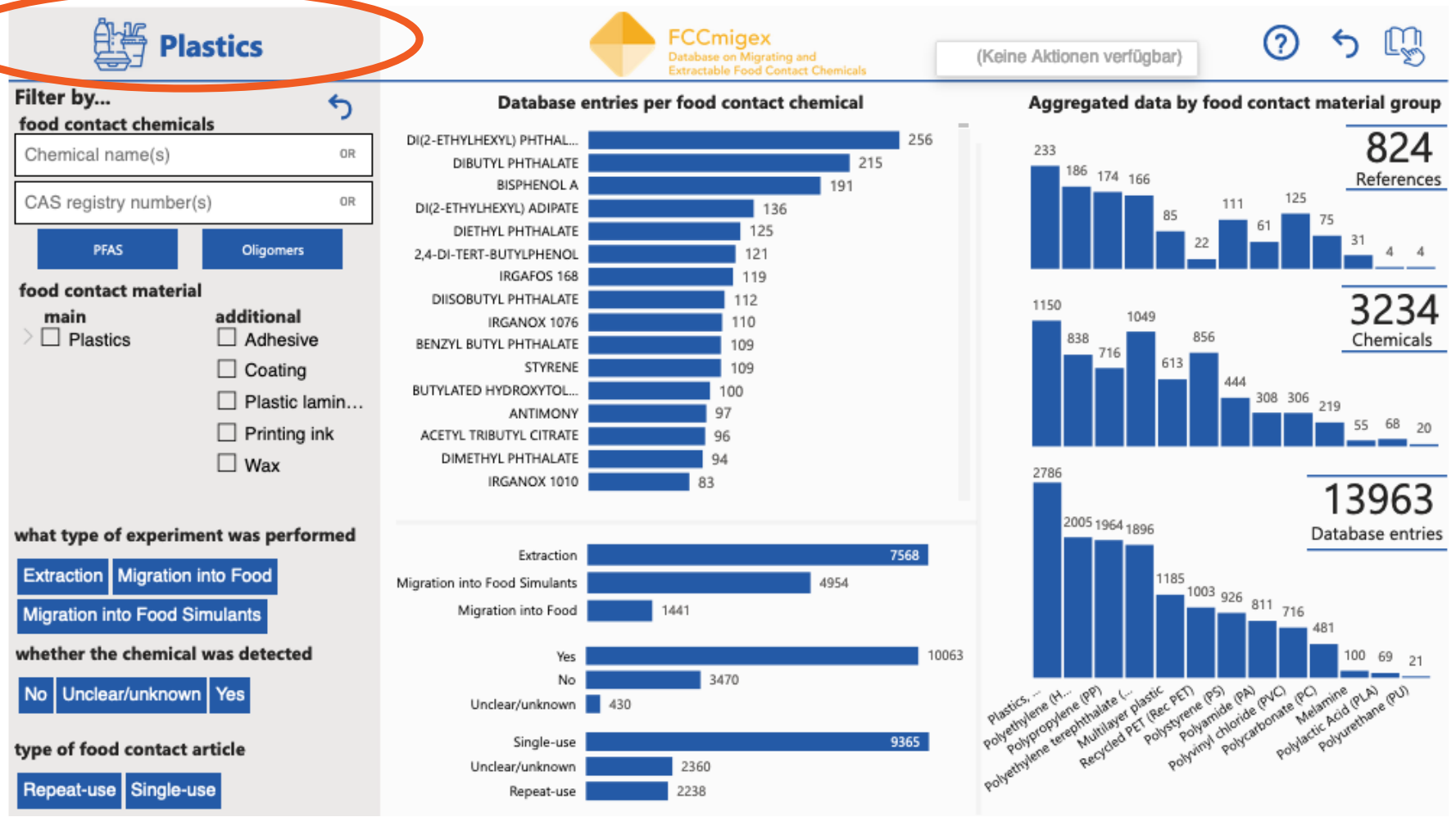
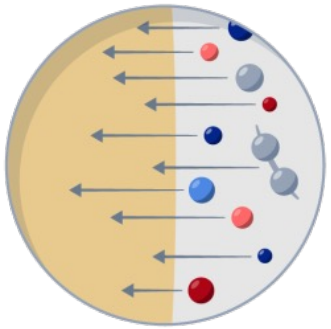
- Petrlík, J.; Brabcova, K.; Ozanova, S.; Beeler, B. (2019): Toxic Soup Flooding Through Consumer Products: Brominated dioxins recycled together with flame retardants into toys and other consumer products – now a widespread problem. DOI: 10.13140/ RG.2.2.17350.52805 und https://ipen.org/sites/default/files/documents/toxic_flood_web2.pdf

Risk Cycle – Extended Producer Responsibility (EPR)

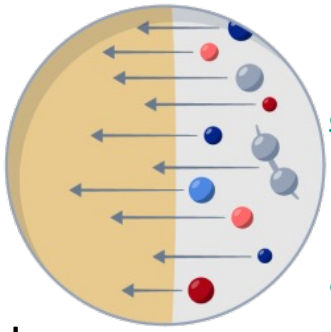




https://www.foodpackagingforum.org/fccmigex

Risk Cycle – it comes out

Many of these pollutants **migrate** from the plastics.



- Additives that are released from plastics and are harmful to consumers (Weber et al. 2023) include the following toxicologically particularly relevant substances/substance groups:
  - plasticizers (especially phthalates),
  - brominated flame retardants,
  - organophosphorus flame retardants,
  - tetrabromobisphenol A (TBBPA),
  - short- and medium-chain chlorinated paraffins
  - Bisphenol A,
  - Bisphenol A dimethacrylate,
  - lead and cadmium,
  - organotin compounds,
  - formaldehyde,
  - acetaldehyde,
  - 4-nonylphenol,
  - methyl tert-butyl ether,
  - benzene and
  - many other VOCs.

https://www.foodpackagingforum.org/fccmigex

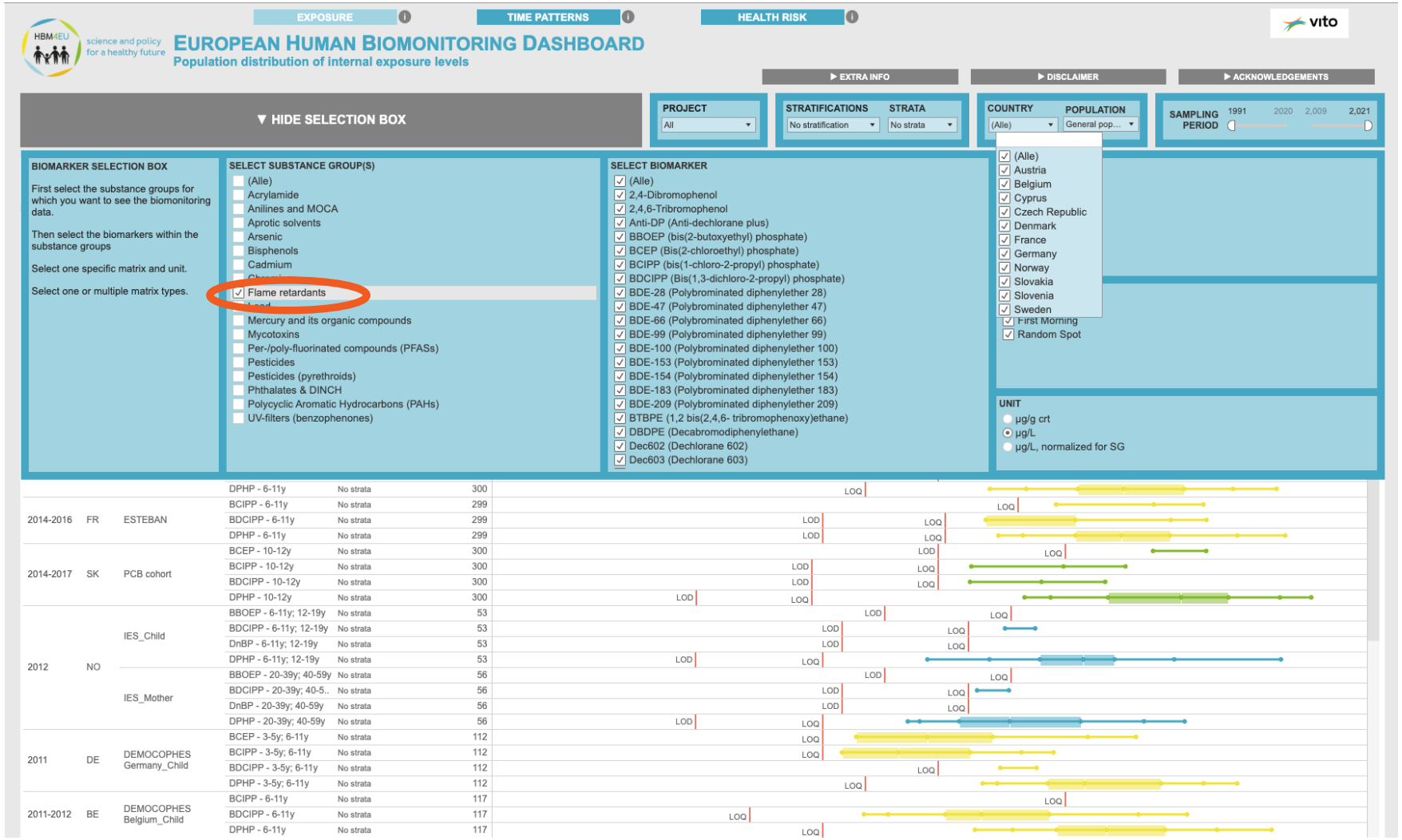
Weber et al. (2023) have also compiled the literature demonstrating that these pollutants are of concern.

Weber, R.; Ashta, N. M.; Aurisano, N.; Wang, Z.; Outters, M.; De Miguel, K.; Schlummer, M.; Blepp, M.; Wiesinger, H.; Andrade, H.; Scheringer, M.; Fantke, P. (2023): Chemicals in plastics: a technical report. United Nations Environment Programme and Secretariat of the Basel, Rotterdam and Stockholm Conventions. Geneva. https://www.unep.org/resources/report/chemicals-plastics-technical-report

Human Biomonitoring

Many additives can be detected **in humans** in worrying concentrations.

Further sources
→ Backup



https://www.hbm4eu.eu/what-we-do/european-hbm-platform/eu-hbm-dashboard/

EU: Regulations against risk cycle

EU legislation has the chemical policy goal of "cleaning up" the cycles. Since 2022, **stricter regulations** have applied in the EU for the use of recyclates for plastic products that come into contact with food (FCM):

- The use of recyclates from PC plastic waste for FCM is generally no longer permitted (except for PET bottles).
- Permitted recyclates must come from the FCM sector and may only be used if they originate from secured cycles ("solely obtained from a product loop which is in a closed and controlled chain, and excludes collection from consumers") (→ Backup).

- European Commission: Food Safety. Legislation. https://food.ec.europa.eu/safety/chemical-safety/food-contact-materials/legislation_en?prefLang=de
- COMMISSION REGULATION (EU) 2022/1616 of 15 September 2022 on recycled plastic materials and articles intended to come into contact with foods, and repealing Regulation (EC) No 282/2008 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32022R1616
- European Commission: Food Contact Materials: Plastic Recycling https://food.ec.europa.eu/safety/chemical-safety/food-contact-materials/plastic-recycling_de

Interim Summary III

- Prohibited additives are further circulated through material recycling. High exposures are the consequence.
- We therefore recommend that the use of PC recyclates (from packaging or technical products) for the manufacture of products with direct contact to humans be discontinued until further notice. This applies in particular to
- Children's toys (EU: regulated),
- Food Contact Material (FCM)/packaging (EU: regulated),
- Indoor products (not yet regulated),
- Synthetic fibers (not yet regulated)

Better control?

- Could the recyclate ban we are proposing be avoided through comprehensive chemical controls?

- Of course, this needs to be discussed (for Germany in the National Circular Economy Strategy – NKWS). We are skeptical as to whether enforcement would be able to manage something like this (variety of substances, internet trade, lack of laboratory equipment).

- A temporary ban on recyclates is much easier to communicate and monitor.

- In our opinion, the outdoor use of recyclates can continue. But no higher pollutant limits than for new products! Enforcement would already be well occupied with monitoring.

Final Summary I

1. The reality of recent decades has shown that the production of new plastic articles has become increasingly sophisticated and demanding in terms of polymers and additive formulations.

   The overall conceptual question therefore arises as to whether material recycling of mixed plastic waste (post consumer) can even be capable of meeting today's requirements for new products on a broad scale.

   We consider this to be **illusory**.

Final Summary II

2. Only 73% of plastic packaging from private households is collected separately. The quantitative material recycling result of this separately collected plastic packaging is meagre (recyclates in new products → Backup).

   The recycled products from this waste are almost exclusively of inferior quality (downcycling, small material-identical substitution, not "virgin") and problematic (risk cycle).

   Depending on their origin, recyclates from technical appliances can be particularly problematic.

Final Summary III

3. Risk cycle: For precautionary reasons, we advise that PC recyclates (from packaging, technical devices, etc.) should no longer be used for new products that are very close to the consumer (especially children's toys, food contact material / packaging, indoor products, textiles).

Final Summary IV

https://www.ifeu.de/fileadmin/uploads/Publikationen/Industrie_Produkte/%C3%96kobilanz_PET-Einweg-LCA-PET-EW-Kreislaufflasche_der_MEG_inkl.CR.pdf

4. We also propose that packaging be better collected **unmixed** in a controlled manner via **extended** deposit and return systems and fed into high-quality material recycling (closed loop, same product types like PET bottles to PET bottles, PET trays to PET trays).

   The existing separate collection of lightweight packaging could – **in the medium term** – be converted into a dry collection of recyclable materials, e.g. to include plastics that were previously not recyclable or difficult to recycle (e.g. technical plastic products) and make them available for chemical recycling.

Final Summary V

5. For many years, a lot of German plastic waste has been legally exported to developing and emerging countries, where it is then "recycled". There are also illegal exports (see, for example, reports from Interpol or the World Customs Union).

   In future, the export of this plastic waste from the EU to non-OECD countries will be banned and the PIC procedure (prior written notification and consent) will be required for exports to OECD countries.
   → Backup

Data from https://dserver.bundestag.de/btd/20/062/2006264.pdf

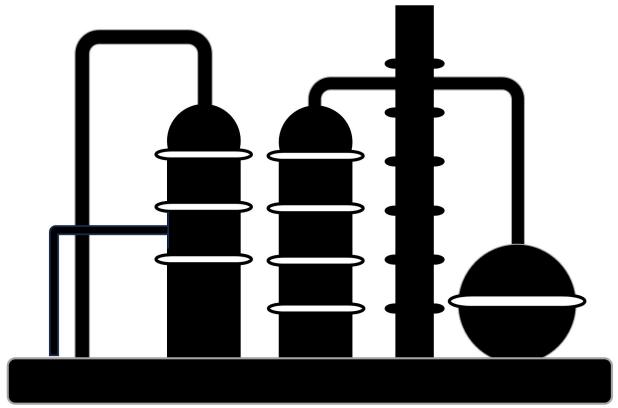
https://www.fao.org/3/y5877e/y5877e.pdf

https://www.consilium.europa.eu/en/press/press-releases/2023/11/17/waste-shipments-council-and-parliament-reach-agreement-on-more-efficient-and-updated-rules/

Side note: Chemical Recycling

Chemical recycling is a generic term for:

- the depolymerization of the polymer(s) into (its/their) monomers, or
- thermal conversion of the plastics into, in particular, pyrolysis oil and then use of the oil as a naphtha substitute for steam cracking, or
- gasification and use of the synthesis gas as a substitute for natural gas, also in the chemical industry (e.g. for steam reforming), or
- solvolysis, hydrogenation, catalysis and much more.



Outlook I

Coalition Agreement, Germany (2021): **"We will include chemical recycling as a recycling option in the Packaging Act."**

Which processes are meant? Let's take pyrolysis:

- Advantage: High-quality recycling, i.e. quality like today's new polymers ("virgin plastic"), no risk cycling.
- The "price" for this positive result: plastic input is "consumed" proportionally for the provision of energy. Additional external energy requirement?
  There is a lack of operating data!
- Criticism: High energy requirement: true, but see "advantage", and the argument applies to many areas of the transformation of the economy (chemical industry, for example).
- Criticism: Pollutant emissions: important issue for waste technology as a whole (including nanoplastic emissions from sorting plants, formation of pollutants during pyrolysis). Solution via BREFs. Quite common procedure in the EU.
- Criticism: No large-scale plants to date: experience from coal chemistry. Much under construction, decentralized infrastructure and (co-)use of existing chemical industrial plants.

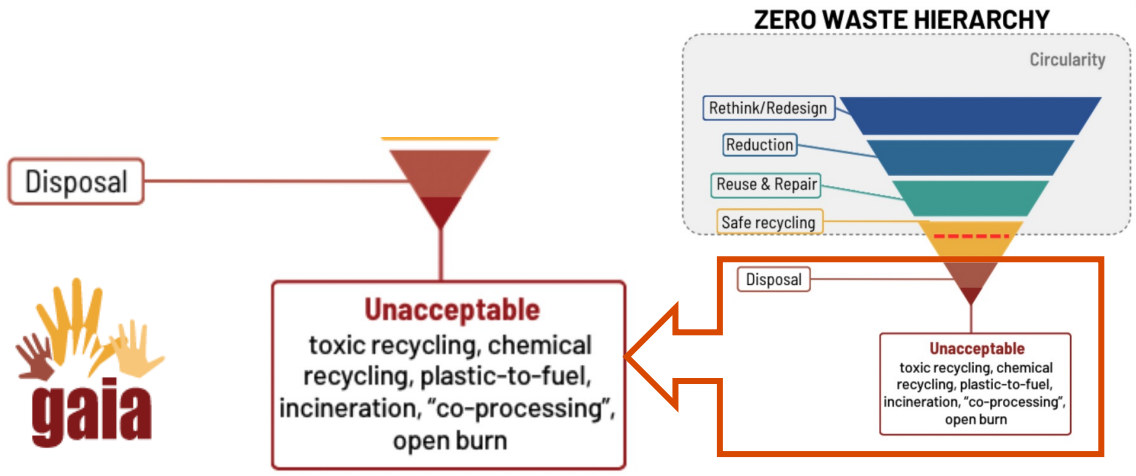
Outlook II

Technologies will change significantly by2050, for example:

- Waste incineration: upgrade, e.g. pre-sorting and CCU/CCS.
- Material recycling: better sorting techniques, chemical controls/ digital product passport/AI, minimum standards § 21, 3 VerpackG/design for recycling.
- Chemical recycling: investment boom, raw material turnaround in the plastics industry, open loop concepts, operating experience, readjustment, emissions/BREFs.

Why not an open-concept hierarchy in performance groups?

- High-quality recycling, for example: Climate neutrality, > 50 % carbon recycling, no relevant pollutant emissions, no risk cycle. Technologies at this level complement each other.
- Intelligent response to "zero waste hierarchy" required!



https://www.no-burn.org/wp-content/uploads/2023/11/INC3-booklet.pdf

Technology openness and optimism

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- Puype, F.; Samsonek, J.; Knoop, J.; Egelkraut-Holtus, M.; Ortlieb, M. (2015): Evidence of Waste Electrical and Electronic Equipment (WEEE) Relevant Substances in Polymeric Food-Contact Articles Sold on the European Market. Food Additives & Contaminants: Part A 32(3): 410–426. https://doi.org/10.1080/19440049.2015.1009499
- Rung, C.; Welle, F.; Gruner, A.; Springer, A.; Steinmetz, Z.; Munoz, K. (2023): Identification and Evaluation of (Non-)Intentionally Added Substances in Post-Consumer Recyclates and Their Toxicological Classification. Recycling 8(1): 24. https://doi.org/10.3390/recycling8010024
- Samsonek, J.; Puype, F. (2013): Occurrence of brominated flame retardants in black thermo cups and selected kitchen utensils purchased on the European market. Food Additives & Contaminants: Part A, 30:11, 1976-1986. https://doi.org/10.1080/19440049.2013.829246

Risk Cycle: Additives, detectable in humans, slide 14

Consequently, these additives can also be detected in high concentrations **in humans** worldwide, see for example (**selection**):

- US EPA (2013): America's Children and the Environment. Third Edition, EPA 240-R-13-001 https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=515537&Lab=NCEE
- Umweltbundesamt (2017): Deutsche Umweltstudie zur Gesundheit, GerES https://www.umweltbundesamt.de/themen/gesundheit/belastung-des-menschen-ermitteln/human-biomonitoring
- HBM4EU: Europäische Human Biomonitoring Initiative (2020): Reporting for first and second set of substances. Deliverable Report AD5.4, WP5 – Translation of results into policies https://www.hbm4eu.eu/wp-content/uploads/2021/03/HBM4EU_AD5.4_Reporting_first_and_second_set_substances_v1.1.pdf
- Umweltbundesamt (2023): Deutsche Umweltstudie zur Gesundheit, GerES V (2014-2017). https://www.umweltbundesamt.de/themen/gesundheit/belastung-des-menschen-ermitteln/umwelt-survey/5-umwelt-survey-von-2013-bis-2016#undefined
- EEA (2023): Public exposure to widely used Bisphenol A exceeds acceptable health safety levels. Press release. Published 14 Sept 2023 https://www.eea.europa.eu/en/newsroom/news/public-exposure-to-bisphenol-a

Packaging: “closed and controlled chain”, slide 15

“**Commission Regulation (EU) 2022/1616**
on recycled plastic materials and articles intended to come into contact with foods will enter into force on 10 October 2022.

…

After the entry into force, further rules will become applicable:

…

- from 10 July 2023, only plastics containing recycled plastic manufactured with a suitable recycling technology may be placed on the market, unless manufactured with a novel technology and in accordance with Chapter IV of the Regulation; the Regulation lays down two suitable technologies:
  - post-consumer mechanical PET recycling; this requires authorisation of individual processes
  - recycling from product loops which are in a closed and controlled chain; this requires the use of a recycling scheme
- from 10 October 2024, quality assurances systems used to collect and pre-process plastic input need to be certified by a third party.”

European Commission: Food Contact Materials: Plastic Recycling
https://food.ec.europa.eu/safety/chemical-safety/food-contact-materials/plastic-recycling_de

Packaging: “closed and controlled chain”, slide 15

Table 1

List of suitable recycling technologies

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Recycling technology number	Technology name	Polymer type (detailed specification in Table 2)	Short description of the recycling technology (detailed specification in Table 3)	Specification of plastic input	Specification of output	Subject to the authorisation of individual processes	Specifications and requirements (reference to Table 4)	Derogations (reference to Table 5)	Recycling scheme applies
1	Post-consumer mechanical PET recycling	PET (2.1)	Mechanical recycling (3.1)	Only PET PCW containing maximum 5 % of materials and articles that were used in contact with non-food materials or substances.	Decontaminated PET, final materials and articles not to be used in microwave and conventional ovens; additional specifications may apply to output from individual processes	Yes	-	-	No
2	Recycling from product loops which are in a closed and controlled chain	All polymers manufactured as primary materials in compliance with Regulation (EU) No 10/2011	Basic cleaning and microbiological decontamination during remoulding (3.2)	Chemically uncontaminated plastic materials and articles produced from a single polymer or from compatible polymers which were used or intended for use under the same conditions of use and solely obtained from a product loop which is in a closed and controlled chain, and excludes collection from consumers	Remoulded materials and articles intended to be used for the same purpose and under the same conditions of use as the materials and articles circulated in the recycling scheme from which the plastic input was obtained.	No	4.1	-	Yes

20.9.2022 EN Official Journal of the European Union

https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32022R1616

Material recycling rates following official documents, slide 19

Material recycling of separately collected PC plastic waste in 2021 = 32.7 %. Figures according to CONVERSIO Market & Strategy GmbH 2021. Calculation point: input final recycler. Plastic packaging 60% of PC waste. LVP packaging (without PET) probably significantly less than 30% when calculating output final recycler.

PET bottle recycling around 15 % of packaging plastics, > 90 % recycling rate.

Aufkommen und Verbleib von Kunststoffabfällen in Deutschland 2021 in Millionen Tonnen (und Prozent)

Anfallort	Gesamt-Kunststoffabfälle*	Post-Consumer-Abfälle**
Stoffliche Verwertung* **	1,98 (35 %)	1,81 (33,2 %)
- werkstofflich	1,96 (34,6 %)	1,78 (32,7 %)
- rohstofflich / chemisch	‹0,03 (0,4 %)	‹0,03 (0,5 %)
Energetische Verwertung	3,66 (64,4 %)	3,60 (66,2 %)
- in Müllverbrennungsanlagen	2,13 (37,4 %)	2,09 (38,4 %)
- als Ersatzbrennstoff / Sonstiges	1,53 (27 %)	1,51 (27,8 %)
Beseitigung / Deponie	0,03 (0,6 %)	0,03 (0,6 %)
Abfallaufkommen insgesamt	**5,67 (100 %)**	**5,44 (100 %)**

*inklusive Kunststoffabfälle aus Produktion und Verarbeitung
**Kunststoffabfälle nach Gebrauch / Endverbraucherabfälle ohne Abfälle aus der Produktion und Verarbeitung
***nach neuem Berechnungspunkt gemäß EU-Durchführungsbeschluss 2019/665 unter Berücksichtigung von Verlustraten bei der Aufbereitung

Quelle: Umweltbundesamt 2023, eigene Zusammenstellung mit Daten der CONVERSIO Market & Strategy GmbH - Stoffstrombild Kunststoffe in Deutschland 2021

https://www.umweltbundesamt.de/daten/ressourcen-abfall/verwertung-entsorgung-ausgewaehlter-abfallarten/kunststoffabfaelle#hohe-verwertungsquoten-

Export of plastic waste from the EU, slide 22

Home > Press > Press releases

Council of the EU Press release 17 November 2023 03:40

Waste shipments: Council and Parliament reach agreement on more efficient and updated rules

This press release was updated on 7 December to add the texts of the provisional agreement

The Council and the European Parliament's negotiators today reached a **provisional political agreement** to update the regulation on shipments of waste.

The revision of the regulation aims to reduce shipments of problematic waste to outside the EU, update shipment procedures to reflect the objectives of the circular economy and improve enforcement.

It sets procedures and control regimes to ensure that international shipments of waste do not pose a threat to human health and the environment, and to promote the use of waste as a resource in a circular economy within the EU.

The deal is provisional pending formal adoption by both institutions.

> Embracing waste as a valuable resource rather than something to dispose of is crucial for our shift to a circular economy. Today's agreement will provide us with the necessary framework to better recover and reuse waste as a secondary material. At the same time, it will help us make sure that the waste we export will not be harmful for the environment and human health. Today's deal is another important step towards the EU's zero-pollution and climate-neutrality goals.
>
> — Teresa Ribera Rodríguez, acting Spanish third vice-president of the government and minister for the ecological transition and the demographic challenge

https://www.consilium.europa.eu/en/press/press-releases/2023/11/17/waste-shipments-council-and-parliament-reach-agreement-on-more-efficient-and-updated-rules/