

Article

Recycling of Post-Consumer HDPE Bottle Caps into New Caps for Food Contact

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Abstract

HDPE caps are collected together with PET bottles, which have been recycled into new bottles for decades. Due to Deposit Return Schemes, the bottle caps are sorted by type and are suitable to be recycled again for sensitive applications e.g., food contact. While there are evaluation criteria for mechanical PET recycling processes, no such evaluation criteria have been published for recycled HDPE caps in food contact. As part of the study, possible evaluation criteria are derived from other polymers or applications and critically discussed. Recycling of post-consumer caps from beverage bottles into new HDPE caps in direct contact with food is realistic even if worst-case considerations on the evaluation criteria are applied. The required cleaning efficiencies are within a range that is technically feasible for today's mechanical HDPE recycling processes. The evaluation criteria can be used for a preliminary assessment of post-consumer HDPE recycle in food contact. Based on the evaluation, the recycling of HDPE caps is to be submitted as a novel technology according to Regulation 2022/1616.

Keywords: circular economy; HDPE bottle caps; recycling; beverage packaging; exposure evaluation



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1. Introduction

The Packaging and Packaging Waste Regulation (PPWR) came into force in January 2025 [1]. According to the European Commission's plans, all packaging in the EU market should be reusable or recyclable by 2030, and the PPWR provides a comprehensive catalogue of measures to achieve the goal of significantly reducing plastic packaging and waste. This requires not only new designs for recyclability and reusability, but also new methods for assessing the chemical safety of recycled food contact materials (FCMs), especially those that have not yet been recycled into new packaging, such as high-density polyethylene (HDPE). Food packaging has very short-lived applications, and it is very important to close the cycle in the (food) packaging sector. The packaging should be processed into new packaging wherever possible. From today's perspective, this is not possible in many areas because the safety requirements for food packaging and consumer exposure are very high. On the other hand, it is required by the PPWR that at least a proportion of recycle will be used in the packaging. With PET bottles, 100% recycle is already possible today due to the low diffusivity of PET, and these are on the market. PET is therefore a prime example of the circular economy [2–4]. For high diffusive polymers, such as polyolefins, it will be much more challenging to achieve a high recycle content without compromising food safety [5–11].

There are many reasons for the successful recycling of PET bottles. Firstly, return systems for PET bottles have been established in many countries. This enables the collection of sufficient quantities and qualities of PET bottles. In Deposit Return Schemes (DRS) only PET bottles in contact with food are collected, thus minimizing contamination with non-food products in the recollected materials. If PET bottles come into contact with non-food contents, only a few post-consumer substances from non-food goods at low concentrations are absorbed into the polymer. In addition, if these substances are absorbed into the PET, the remigration into food or beverages in the second life of the bottle is low [3]. Recycling multiple times without loss of quality is also possible in the case of PET [4]. Due to these very favourable conditions, many PET recycling processes have been established worldwide. The American and European Food Safety Authorities (FDA and EFSA) have therefore assessed many PET recycling processes and found no health risks for the consumers. According to the new Recycling Regulation 2022/1616, PET recycling processes with EFSA evaluation are consequently categorized as “suitable technologies” [12].

Together with the PET bottles, the caps also accumulate during recollection, shredding and washing. This is due to the fact that PET bottles are mostly recollected together with their HDPE caps. To further reduce the loss of caps to the environment and increase collection volumes, Directive (EU) 2019/904 [13], which came into force in July 2024, requires that caps and lids made of plastic may be placed on the market only if the caps and lids remain attached to the containers during the products’ intended use stage. This means that the caps of beverage bottles cannot be removed from the bottle and were completely recollected together with the PET beverage bottles. An important side effect is that if the caps are collected via DRS, they are automatically compliant with Regulation 10/2011 [14], because food bottles have to be compliant in the first life with Regulation 10/2011, and on the other hand, non-food bottles are rejected in DRS collections. Compliance with Regulation 10/2011 is a basic requirement for the recyclate to be reused in contact with food. Like PET bottles, bottle caps collected via DRS are therefore ideal material for closing the cycle to new bottle caps. Nevertheless, no industrial scale recycling processes for HDPE bottle caps into new bottle caps have been established to date. However, there has already been a submission for food safety evaluation by the EFSA in accordance with the former Recycling Regulation 282/2008 [15]. In this application, a process was described for the recycling of HDPE caps into new bottle caps. The authorization process, however, has not yet been successful [16]. This was a bitter setback for efforts to achieve a circular economy. On a positive note, however, EFSA has already published their thoughts on the assessment criteria for the safe recycling of bottle caps into new caps for beverages in this inconclusive opinion. Even EFSA has not yet published final assessment criteria for recycling of HDPE bottle caps similar to those of PET mechanical recycling processes [17,18]; assessment criteria can be derived from EFSA opinions that have already been published, e.g., inconclusive HDPE caps [16] and mechanical PET recycling for beverage bottles [17,18], as well as the recycling of milk bottles into new milk bottles [19]. The latter, however, was also in an inconclusive opinion published by EFSA. From this it can be deduced whether HDPE recyclates are at all suitable for direct contact with food and whether consumer protection is sufficiently ensured.

Typically, recycling of HDPE bottle caps is carried out as follows: The HDPE flakes from the bottle caps are separated from the PET regrind during recycling in a swim/sink separation process. After separation, the HDPE bottle cap flakes pass a washing line. The final product is washed HDPE flakes. This material then often passes through an optional flake colour sorter as a final quality control. Subsequently, the HDPE flakes are typically extruded to pellets and further decontaminated by the use of high temperatures and a vacuum, air or inert gas (so-called super-clean recycling or deodorization processes). The

cleaning efficiency of the super-clean recycling processes is determined by a so-called challenge test. Within this challenge test, the input material is artificially contaminated with model substances (so-called surrogates). Subsequently, the contaminated flakes are processed with the recycling process. After each of the individual process steps, samples are drawn and analyzed due to their residual contamination levels of the surrogates. From the difference between the (artificial) initial contamination level and the residual contamination in the final product, the cleaning efficiency of each individual surrogate can be calculated.

Post-consumer recycled HDPE for use in bottle caps has not yet been evaluated (successfully) by the EFSA. Therefore, according to Regulation 2022/1616, the use of post-consumer HDPE in direct food contact can be considered as “Novel technology” [12]. However, evaluation criteria for the assessment of recycled bottle caps into new bottle caps have not been published to date by EFSA or other competent authorities.

The aim of this study was to review the scientific literature for HDPE recyclates and to propose evaluation criteria for the evaluation of post-consumer recyclates from HDPE caps for application in direct contact with mineral water and beverages. Based on the results, the minimum cleaning efficiencies of the super-clean or deodorization processes should be derived. In addition, knowledge gaps should be identified. The paper is organized as follows: Firstly, the material flows were analyzed; then, the literature on possible contaminants in the input materials was evaluated and the possible input contamination was derived. Possible evaluation criteria were then proposed, and, in the final step, the minimum cleaning efficiencies of the recycling processes were calculated. The steps were subjected to a critical discussion.

2. Results

2.1. Input Control

Existing feedstock streams material can be used as input materials. For example, PET bottles were recollected together with the HDPE caps from DRS. These DRS require consumers to pay a deposit when purchasing a beverage in a PET bottle and receive a refund when the bottle is returned for recycling. This input is exclusively food contact bottles, controlled by bar codes, artificial intelligence and a special deposit logo on the bottles. Non-food bottles are rejected in the deposit return machines. The input material for the super-clean recycling process is therefore in compliance with Regulation 10/2011, because the PET bottles and HDPE caps were in food contact in their first life [14]. In addition, DRS is a controlled recollection system in compliance with Article 6 of Regulation 2022/1616 [12]. Both are important prerequisites for ensuring that the beverage caps are suitable for contact with food again and that the level of contamination is not too high. This makes DRS an ideal return system for food packaging which can be recycled into new packagings for sensitive applications, such as food. DRS are currently installed in Europe in Austria, Croatia, Denmark, Estonia, Finland, Germany, Iceland, Lithuania, the Netherlands, Norway and Sweden. Further countries, like France and Spain, are discussing or decided the implementation of DRS for the recollection of PET beverage bottles. The implementation of DRS is aimed at increasing the collection and recycling rates of PET bottles and other beverage containers, contributing to environmental sustainability.

2.2. Contamination Levels

Data on the input contamination levels of post-consumer HDPE beverage bottle caps are not available in the scientific literature. Only data from recollected HDPE milk bottles collected within curbside collections in the UK were published [20]. Within this study, 2 out of 24,000 HDPE milk bottles show hints of misuse contamination. The maximum concentration found in the milk bottles was about 6500 mg/kg. This results in an inci-

dence of misuse of 0.0083% and an average contamination of substances from misuse of 0.54 mg/kg in washed HDPE flakes from milk bottles from the UK market. EFSA followed this scientific publication [20] and considered an initial concentration of 0.5 mg/kg in milk bottles collected in UK as worst-case [20]. In addition, even the detected substances from misuse were identified as (well known) solvents; EFSA considers all substances from misuse as genotoxic.

Regarding the incidence of misuse of PET bottles (with their HDPE bottle caps), it was found within the Recyclability Project that the incidence of misuse of PET bottles in Europe is 0.03–0.04% [21]. This means that 3 to 4 bottles out of about 10,000 PET bottles show hints of misuse. This incidence was determined in a screening of washed PET flakes over several years. EFSA used this incidence for the assessment of PET mechanical recycling processes [17,18]. If it is assumed that every PET bottle has an HDPE cap, the incidence determined for PET bottles is the same as for their HDPE caps.

Assuming a cap weight of 3 g, 9–12 g of contaminated HDPE flakes might be found in 30,000 g HDPE flakes (or 300–400 g of contaminated flakes in 1 t of post-consumer washed flakes). Assuming a concentration of 1000 µg/g in the contaminated flake, the absolute amount of 300–400 mg chemicals from misuse can be found in 1 t of HDPE cap flakes, which is 0.3–0.4 mg/kg in washed flakes from PET beverage bottle caps. This value is from a purely statistical point of view and is in good agreement with the 0.5 mg/kg of the HDPE milk bottles [19]. Therefore, an initial concentration of post-consumer substances in HDPE bottle caps of 0.5 mg/kg might be a suitable initial concentration until better analytical data are available. It is important to note that neither the UK milk bottle study nor the PET Recyclability Project investigated input materials from DRS. In both projects the bottles were collected via plastic curbside collections. The milk and beverage bottles therefore had contact with other (non-food) packaging, and, due to cross-contamination, the milk and beverage bottles might be contaminated with untypical substances for food packaging. It is therefore most likely that the contamination levels in plastic curbside collections are higher than those found in DRS.

As mentioned above, EFSA assumed that the input contamination level of 0.5 mg/kg used includes genotoxic compounds [17–19]. However, it is most unlikely that the input material from post-consumer PET bottle caps collected by DRS contains a homogenous contamination level of 0.5 mg/kg of genotoxic compounds. The contamination of post-consumer washed HDPE flakes from beverage bottle caps with genotoxic compounds must be, if at all, much lower. This assumption is supported by the fact that the consumer has no genotoxic compounds available at home which can be brought into contact with the PET bottles and HDPE caps. EFSA mentioned in their evaluation criteria for mechanical PET recycling processes that “genotoxic compounds are generally not allowed to be placed on the market in consumer products and, therefore, the probability of a contamination of the post-consumer PET by misuse with substances classified as genotoxic, if any, is low” [18]. In addition, EFSA mentioned that “functional groups associated with genotoxicity of molecules are often highly reactive. If they were present, they would be expected to react in PET during the recycling process at high temperatures. This would decrease their potential residual concentration and, hence, their migration” [18,22]. It is therefore most unlikely that the substances from misuse or cross-contamination are genotoxic. On the other hand, genotoxic compounds might be formed during recycling, for example, as degradation products from the polymer, from polymer additives or pigments [23,24]. Also, other NIAS can be detected in post-consumer recycled HDPE [25–31].

2.3. Proposed Criteria for the Evaluation of Recycled Bottle Caps

Criteria for the assessment of post-consumer recyclates in direct contact with food can be derived from the EFSA opinions which are already published [16–19]. These can then be transferred to the recycling of post-consumer HDPE caps. This allows a preliminary assessment of HDPE recycling processes even if EFSA or other competent authorities have not yet published any criteria for mechanical recycling of HDPE bottle caps. As a disclaimer, the proposed criteria should be understood as a suggestion for a provisional assessment of mechanical recycling processes. In the end, the assessment criteria of recycled HDPE in contact with food is of course the decision of EFSA or competent authorities.

The first point is that the input material is compliant with Regulation 10/2011. This means that all monomers, additives and processing aids are listed in Annex I and II of Regulation 10/2011 and that their migration is in line with the specific migration limits. As mentioned above, this is due to the fact that the disposable material is collected via a DRS. All materials were therefore in contact with food in their first life and therefore also in compliance with Regulation 10/2011. In the second step, EFSA assessed the concentration of substances from the first life, as well as the possible misuse of PET bottles (and their caps) for the storage of chemicals. There are only sparse data on this in the scientific literature. From the discussion in the previous chapter, however, possible input concentration levels were derived from the data generated for PET bottles to 0.5 mg/kg as initial concentration of “misuse” contaminants. In the third step, EFSA evaluates consumer exposure. EFSA assumes that substances from misuse are genotoxic and uses the lowest limit value according to the Threshold of Toxicological Concern (TTC) concept, which is 0.0025 µg per body weight (b.w.) and per day [32,33]. Furthermore, EFSA considers that mineral water is consumed also by very small infants and assumes that an infant with 5 kg b.w. drinks 1.3 L (260 mL per kg b.w. per day, Scenario A in [18]) of water from a bottle containing 100% recyclate. This results in an exposure for the infant of 0.00962 µg/L [18]. This value can be considered as the maximum migration from either the PET bottle or from a HDPE bottle cap into mineral water (worst-case). For other beverages (except mineral water), EFSA scenario B can be applied [18]. In this case, a toddler with 12 kg b.w. drinks 960 mL (80 mL per kg b.w. per day) beverages per day. The exposure is more than 0.0313 µg/L, which is a factor of 3.25 higher compared to mineral water (scenario A). In the fourth step, the migration value is translated into a maximum packaging material concentration which corresponds to a migration of 0.00962 µg/L or 0.0313 µg/L, respectively. For this migration process, EFSA assumes contact conditions of 365 d at 25 °C [17,18]. Due to the fact that such low migration limits are hard to measure, EFSA is using migration modelling instead. The modelling parameters are published for HDPE and generally accepted by authorities [19,34]. According to EFSA, the migration model overestimates the real migration into food. Therefore, EFSA applied an overestimation factor of 2 for calculations of HDPE [19]. The maximum tolerable migration from the bottle cap into mineral water and beverages increased by the same factor to 0.0192 µg/L (mineral water) and 0.0626 µg/L (other beverages), respectively. Furthermore, it was assumed that the partition coefficient is $K = 1$ which means that all migrants are well soluble in mineral water and beverages, which might not be the case for all substances. Especially for high molecular weight and non-polar stances, it is expected that the solubility in water and beverages will be low. Therefore, $K = 1000$ is also used for the calculation in this study, which represents the low solubility of the migrants in water and beverages [34]. In this way, maximum concentrations in HDPE can be established which would not lead to exceeding a certain migration value of 0.0192 µg/L (mineral water) and 0.0626 µg/L (other beverages). The intended application of the HDPE recyclate is beverage bottle caps with storage conditions up to 365 days at room/ambient temperature (25 °C), including hot filling, as used by EFSA

for the evaluation of recyclates in PET bottles [17,18]. The calculations were performed using $A_p' = 14.5$ and $\tau = 1577$ K, which are the modelling parameters for HDPE [19,34]. The maximum concentrations of the applied surrogates were calculated for a food package with a 1 l volume bottle and with an inner surface area of the cap of 7.40 cm². The density of HDPE was assumed to be 0.95 g/cm³. The thickness of the cap in the region with food contact was assumed to be 1250 µm. The maximum concentrations in the HDPE caps for water applications (migration 0.0192 µg/L) and other beverages (migration 0.0626 µg/L) are shown in Figure 1 as a function of molecular weight.

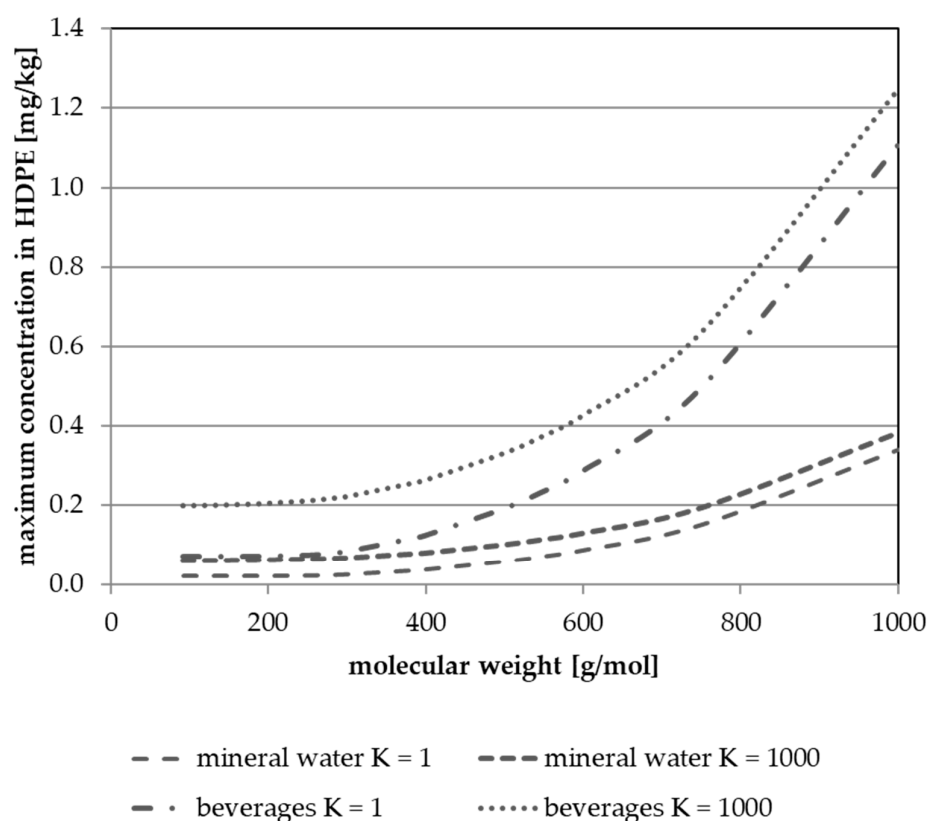


Figure 1. Maximum concentration in beverage caps corresponding with migration levels of 0.0192 µg/L (mineral water) and 0.0626 µg/L (other beverages) after storage for 365 days at 25 °C (partition coefficient $K = 1$ (good solubility) and $K = 1000$ (low solubility), density of HDPE 0.95 g/cm³, thickness 1250 µm, surface area 7.40 cm²).

2.4. Minimum Cleaning Efficiencies

The minimum cleaning efficiencies of the surrogates in a challenge test can be derived from the maximum concentrations of the substances in the HDPE cap (Figure 1) with the maximum contamination level in post-consumer HDPE recyclates from misuse. The latter was assumed to be 0.5 mg/kg in HDPE (see Chapter Contamination Levels). In the first approach, the migration was calculated into water or beverages and the diffusion process to the environment is blocked. Therefore, the diffusion process occurs only to the inside of the cap/bottle but not to the environment. This (unrealistic) approach has been used in EFSA's HDPE milk bottle opinion [19]. In a second approach, the diffusion of the surrogates to the environment as well as to the mineral water and beverage was considered. In addition, partition coefficients of $K = 1$ (good solubility) as well as $K = 1000$ (low solubility) were calculated. As a result, the required cleaning efficiencies for molecules above approximately 400 g/mol remain the same. Only for smaller molecules, the minimum cleaning efficiency is significantly lower for the second approach due to the loss of substances to the environment (91.3% versus 95.6%, scenario A, and 71.5% versus 85.8%, scenario B). The results for the

minimum cleaning efficiencies are given in Table 1 (mineral water, scenario A) and Table 2 (beverages, scenario B) as well as in Figure 2. These minimum cleaning efficiencies must be established by the HDPE super-clean recycling or deodorization process in order to comply with the above-mentioned evaluation criteria.

Table 1. Minimum cleaning efficiencies for 100% recyclate content in mineral water applications (scenario A). Storage conditions 365 days at 25 °C, thickness 1.25 mm, density of HDPE 0.95 g/cm³, food contact surface 7.4 cm².

Surrogate	Molecular Weight [g/mol]	Minimum Cleaning Efficiency [%]			
		Migration Only Inside K = 1	Migration Only Inside K = 1000	Migration Inside and Outside K = 1	Migration Inside and Outside K = 1000
toluene	92	95.6	87.7	91.3	83.2
	100	95.6	87.7	91.3	83.2
chlorobenzene	113	95.6	87.6	91.3	83.1
chloroform	119	95.6	87.6	91.3	83.1
limonene	136	95.6	87.6	91.3	83.1
methyl salicylate	152	95.6	87.5	91.3	83.1
phenyl cyclohexane	160	95.6	87.5	91.3	83.0
benzophenone	182	95.6	87.4	91.3	82.9
butyl salicylate	194	95.6	87.3	91.3	82.9
methyl palmitate	200	95.6	87.3	91.3	82.9
	250	95.4	86.9	91.3	82.6
	271	95.3	86.7	91.3	82.5
	291	95.0	86.4	91.3	82.4
	298	94.9	86.3	91.3	82.4
DEHP	391	92.7	84.0	90.8	81.9
TEHTM	400	92.4	83.7	90.7	81.7
	500	88.2	79.6	87.9	79.2
	548	85.7	77.0	85.5	76.9
	600	82.4	73.8	82.4	73.8
	750	69.6	61.0	69.6	61.1
	1000	32.1	23.5	32.1	23.5

Table 2. Minimum cleaning efficiencies for 100% recyclate content in beverages applications (scenario B). Storage conditions 365 days at 25 °C, thickness 1.25 mm, density of HDPE 0.95 g/cm³, food contact surface 7.4 cm².

Surrogate	Molecular Weight [g/mol]	Minimum Cleaning Efficiency [%]			
		Migration Only Inside K = 1	Migration Only Inside K = 1000	Migration Inside and Outside K = 1	Migration Inside and Outside K = 1000
toluene	92	85.8	59.8	71.5	45.2
	100	85.8	59.8	71.5	45.2
chlorobenzene	113	85.8	59.7	71.5	45.0
chloroform	119	85.8	59.7	71.5	45.0
limonene	136	85.8	59.6	71.5	44.9
methyl salicylate	152	85.8	59.4	71.5	44.7
phenyl cyclohexane	160	85.8	59.2	71.5	44.6
benzophenone	182	85.7	59.0	71.5	44.3
butyl salicylate	194	85.7	58.7	71.5	44.1
	200	85.6	58.6	71.5	44.1

Table 2. Cont.

Surrogate	Molecular Weight [g/mol]	Minimum Cleaning Efficiency [%]			
		Migration Only Inside K = 1	Migration Only Inside K = 1000	Migration Inside and Outside K = 1	Migration Inside and Outside K = 1000
methyl palmitate	250	85.1	57.4	71.5	43.3
	271	84.5	56.6	71.5	42.9
	291	83.7	55.7	71.5	42.7
	298	83.4	55.4	71.5	42.6
DEHP	391	76.0	47.9	70.0	40.8
	400	75.1	47.0	69.5	40.5
TEHTM	500	61.5	33.5	60.5	32.1
	548	53.2	25.1	52.8	24.8
	600	42.6	14.5	42.6	14.5
	750	0.9	0	0.9	0
	1000	0	0	0	0

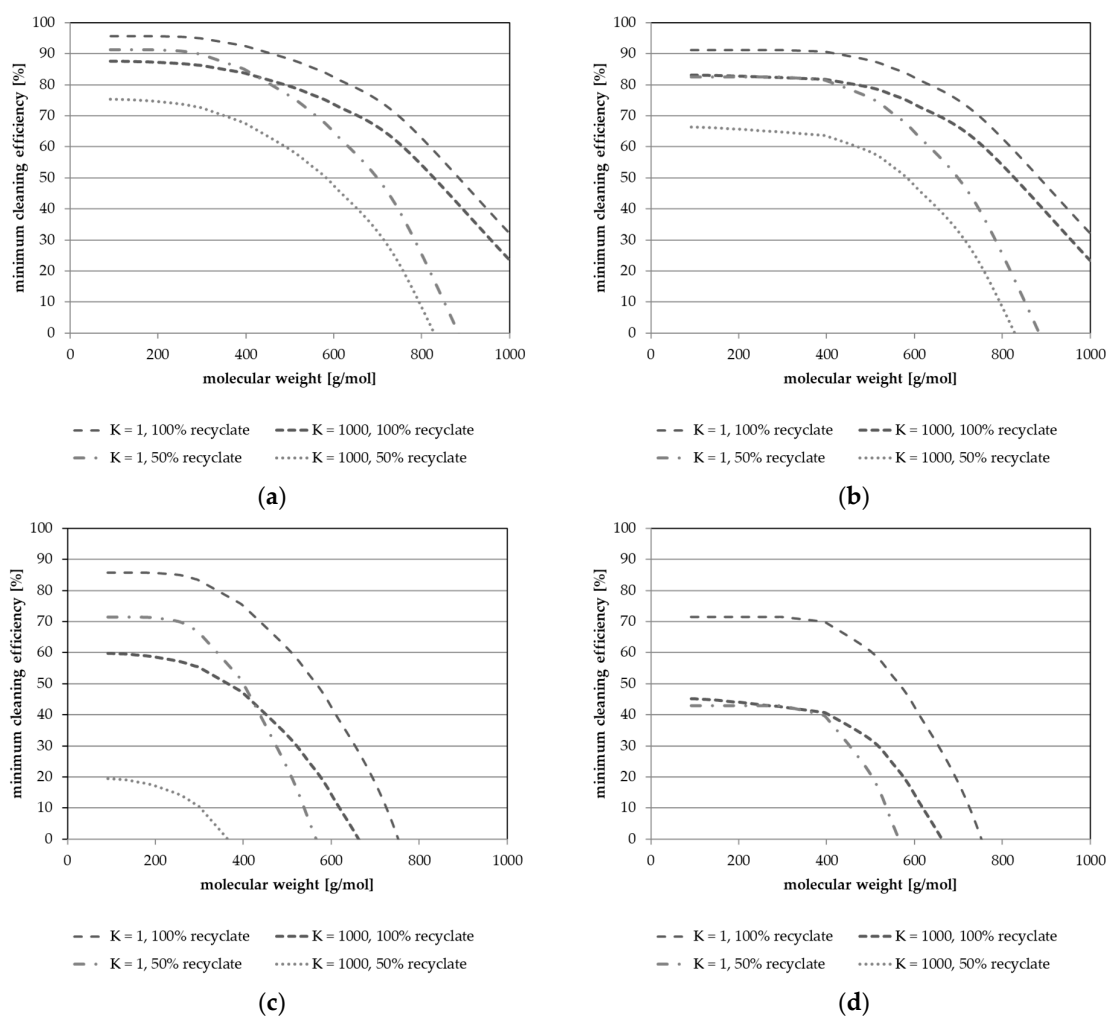


Figure 2. Minimum cleaning efficiencies for 100% and 50% recyclate content as a function of molecular weight. (a) Migration into water (scenario A), migration to environment not considered, (b) migration into water (scenario A), migration to the outside considered, (c) migration into beverages (scenario B), migration to environment not considered, (d) migration into beverages (scenario B), migration to the outside considered. Storage conditions 365 days at 25 °C, thickness 1.25 mm, density of HDPE 0.95 g/cm³, food contact surface 7.4 cm².

3. Discussion

The recycling of PET bottles into new food contact material has been established for several years. PET is a low diffusive polymer which results in a (very) low migration if some traces of post-consumer substances or substances from potential misuse of the PET bottles for storage of hazardous substances remain in the packaging materials after decontamination. In contrast to that, HDPE (or polyolefins in general) is a high diffusive polymer. This means that traces of contaminants after decontamination will migrate into HDPE packed food at much higher levels than found for PET. Regarding consumer protection, post-consumer recyclates must be at a similar safety level as packaging made from virgin polymers. The assessment of recyclates is therefore subject to strict conditions by the competent authorities. Evaluation criteria for mechanical recycled PET have been published [17,18]. However, criteria for the evaluation of post-consumer HDPE caps which are recycled back into new caps with food contact are not available to date.

Within the study, evaluation criteria have been proposed based on the existing publications of EFSA. The initial concentrations of post-consumer substances in the input material of decontamination processes are only roughly known at the moment. However, they can be derived from the incidence of misuse from PET bottles, as well as from similar recycling streams like HDPE milk bottles. The concentration of 0.5 mg/kg was derived from plastic curbside collections and not from DRS. There are no data in the scientific literature for HDPE caps collected from DRS, but it can be assumed that controlled DRS collections, where only food contact materials are recollected, result in much lower contamination levels than plastic curbside collections, where food contact materials are mixed with non-food plastics. The risk of cross-contamination during recollection in mixed collections is most probably much higher. The applied 0.5 mg/kg initial contamination level used in this study to calculate the minimum cleaning efficiency can be therefore considered as the worst case.

As another worst-case scenario, the whole initial contamination level of 0.5 mg/kg is considered as genotoxic. As the consumer typically does not have genotoxic substances available to be filled in bottles with HDPE caps, this can also be assumed as the worst case. If genotoxic compounds can be excluded in the input of HDPE mechanical recycling processes, the exposure increases from 0.0025 µg per kg body weight per day used in the calculation of the minimum cleaning efficiencies to 1.5 µg per kg body weight per day (substances in Cramer Class III). This increases the maximum tolerable migration value by a factor of 600 and leads to a maximum migration value of 11.5 µg/L for mineral water applications (scenario A) and to 37.5 µg/L for other beverages (scenario B).

The consumption of mineral water of infants as well as other beverages for toddlers were taken from the EFSA approach with 1.3 L and 0.96 L per day. These exposure scenarios are already specified by the EFSA in the assessment criteria for mechanically recycled PET [18] and were not changed at all in this study. In addition, it was assumed that the complete amount is consumed in packaging materials with HDPE caps. However, mineral water and beverages are also available in, e.g., glass bottles with metal caps or refillable PET bottles with caps made out of polypropylene (PP). Other packaging materials or even caps made from virgin HDPE are therefore completely disregarded in this approach, which of course means the worst-case scenario.

As mentioned before, HDPE is a high diffusive polymer. A major consequence of the high diffusivity of HDPE is that with long storage times (e.g., 365 days), the post-consumer substances are (nearly) completely transferred into the food and equilibrium between the concentration in the HDPE material and the concentration in food is (almost) reached. This means that diffusion coefficients play a minor role. This is obvious from Tables 1 and 2 where the minimum cleaning efficiencies for most of the surrogates are (nearly) the same. Only for substances with a molecular weight of above approx.

300 g/mol are lower minimum cleaning efficiencies required. When reaching the equilibrium, the partition coefficient K plays the major role in migration. Consequently, the partition coefficients should be taken into account in migration calculations.

In general, the migration model used in this study is overestimating for all polymers [34]. This is due to the fact that the diffusion coefficients are overestimated. The margin of overestimation, however, depends on the molecule size and its polarity and is not known without experimentally determined diffusion coefficients and partition coefficients. In the EFSA evaluation criteria, calculations always assumed good solubility of the substances in the beverage, which is reflected in the calculations with a partition coefficient of $K = 1$. High molecular weight substances are probably low or hardly soluble in water and beverages. It is most unlikely that high molecular weight molecules, like the surrogates DEHP and TEHTM, are highly soluble in mineral water, beverages and juices at ambient temperatures. Therefore, the calculations should not be performed with $K = 1$ exclusively. In contrast to the diffusion coefficients, however, the partition coefficients between the polymer and water or beverages cannot be predicted. It is therefore not possible at the moment to use a realistic partition coefficient. Hence, $K = 1000$ is typically used for poorly soluble substances [34]. It would certainly make sense to determine the partition coefficients between HDPE and water or beverages experimentally in order to be able to use realistic partition coefficients in the calculations. As shown in Tables 1 and 2, as well as in Figures 1 and 2, where $K = 1$ and $K = 1000$ were compared, it can be seen that the partition coefficient has a considerable influence on the minimum cleaning efficiency.

Another consequence of reaching the equilibrium is that migration to the side facing away from the food also plays a role. Migration into the environment reduces the concentration of potential contaminants in the bottle cap. Diffusion to the environment was therefore also taken into account in this study when calculating the minimum cleaning efficiencies. In the end, this results in a factor of 2 in the cleaning efficiencies for low molecular weight surrogates which are (nearly) reaching the equilibrium. For bigger molecules, the effect is lower. An indirect consequence of the high diffusivity is also that the geometry of the cap has an influence on the result. In this study, a closure thickness of 1.25 mm and an inner surface area of 7.4 cm² were used for the calculations. Both thickness and inner surface were provided by a closure manufacturer for HDPE caps for mineral water and beverages. If the actual layer thickness and surfaces deviate significantly from this thickness, new calculations should be made. The thread of the closure was not taken into account in the calculations as it is not in direct contact with the food. Due to the different designs of HDPE caps, it is very difficult to make general statements about migration.

Based on the discussion, it is obvious that the assessment of HDPE cap with post-consumer recyclate is complex and difficult to evaluate. In order to avoid these difficulties in the assessment of safety, the data in this study were generated under worst-case considerations. This means that the migration and thus the exposure of the consumer in this study are significantly higher compared to the real exposure of the consumer. Nevertheless, the minimum cleaning efficiencies in Tables 1 and 2 are achievable with today's mechanical recycling technologies on HDPE. Due to the worst-case approach, however, it is also advisable to determine the true migration experimentally, even if this will be very difficult due to the low migration limits to be achieved.

4. Materials and Methods

The work was mainly a literature review. Experimental work was not conducted as part of this study. However, diffusion modelling was applied to predict the migration from the recyclate containing FCMs. Diffusion modelling was performed using the AKTS SML software version 4.54 (AKTS AG, Siders, Switzerland). The program uses finite element

analysis [35]. The modelling parameters used by EFSA are given in the modelling Guide of the European Joint Research Centre JCR [34]. The modelling conditions (time, temperature, polymer density) are the same as given in the EFSA evaluations of mechanically recycled polymers [16–19].

5. Conclusions

Recycling of post-consumer caps from beverage bottles into new HDPE caps in direct contact with the food is realistic even if worst-case considerations on the evaluation criteria are applied. The required cleaning efficiencies are within a range that is technically feasible for today's mechanical HDPE recycling processes. DRS are ideal collection systems for the circular economy. Firstly, it can be shown that the input materials for recycling already comply with Regulation 10/2011 and Article 6 of Regulation 2022/1616, which is a fundamental prerequisite for use in the sensitive food packaging sector. Secondly, contamination of the input material with substances from other packaging (cross-contamination) is minimized in DRS collections.

The results of the study show that the assessment recycled HDPE in sensitive areas like food packaging is complex, because lots of factors are influencing the result. It is difficult, but not impossible, to achieve criteria based purely on calculations based on worst-case scenarios. Therefore, the calculations should be supported by experimental migration measurements in real products. However, this is difficult and costly due to the low detection limits to be achieved.

The reason for the low detection limits lies in the worst-case assumptions of the evaluation criteria. If a worst-case factor is included at each critical point, then the worst-case factor of the overall evaluation is the multiplicative of the individual factors. This quickly results in very high safety factors in the evaluation, which (unnecessarily) increase the minimum cleaning efficiencies. The evaluation criteria used in this study should be understood as an initial suggestion and should be reconsidered, and possibly made more realistic, as more knowledge is gained on HDPE bottle cap recycling.

Partition coefficients between HDPE and water or beverages should be determined experimentally in order to use the realistic K values for the calculation of migration. The approach in this study shows that the partition coefficient has a large influence on the minimum cleaning efficiency. Realistic partition coefficients K are necessary for a more realistic assessment of consumer safety. However, even if the worst-case partition coefficient of $K = 1$ is used, it can be shown with the applied conditions that the recycling of HDPE caps to new caps in direct contact to food can be ensured.

According to Recycling Regulation 2022/1616 [12], recyclers must submit a novel technology if post-consumer bottle caps will be recycled into new bottle caps. However, evaluation criteria for the safety evaluation are not yet available. The results of this study provide initial indications that it is possible to recycle HDPE caps into new bottle caps. The final decision on whether a novel technology becomes a suitable technology ultimately lies with competent authorities and the European Commission.

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