Fraunhofer IVV

Test report

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Challenge test on a recycling process for post-consumer HDPE

Commissioning party:	Versalis S.p.A. Viale Alcide De Gasperi, 2 20097 San Donato Milanese (MI) Italy
Project number:	PA-1288c-24 rev.
Start of project:	19.09.2024
Samples:	03.09.2024 (HDPE pellets for contamination) 16.12.2024 (challenge test samples)
Date of report:	09.10.2026

The results refer solely to the tested samples.

1 Background and objectives

The customer wants to recycle post-consumer HDPE into new packaging applications (e.g. milk bottles or beverage caps). The decontaminated post-consumer recyclate will be in direct contact to food. The most important parameter of the recycling concept is the cleaning efficiency of the applied recycling process towards potential post-consumer substances.

Aim of the study is the determination of the cleaning efficiency of the investigated HDPE super-clean process.

2 Model contaminants (surrogates)

Table 1 gives details of the model contaminants that were used.

Table 1: Model contaminants used for the challenge test with details of their molecular weight, functional groups and physical properties

Substance	M_W[a]	Functional groups	Properties
Toluene	92.1	Aromatic hydrocarbon	volatile, non-polar
Chlorobenzene	112.6	Aromatic hydrocarbon, halogen-containing	volatile, polar
Limonene	136.2	Aliphatic hydrocarbon	volatile, non-polar
Phenylcyclo-hexane	160.3	Aromatic hydrocarbon	low volatility, non-polar
Benzophenone	182.2	Aromatic ketone	low volatility, polar
Butyl salicylate	194.2	Aliphatic ester	non-volatile, non-polar
Methyl palmitate	270.5	Aliphatic ester	non-volatile, medium-polar
Diethylhexyl adipate DEHA	370.6	Aliphatic ester	non-volatile, medium-polar
Tris(ethylhexyl) trimellitate TEHTM	546.8	Aromatic ester	non-volatile, medium-polar
Ethylhexyl triazone (Uvinul T150)	823.1	Aromatic ester	non-volatile, medium-polar

[a]Molecular weight in g/mol

3 Contamination procedure

100 kg of HDPE pellets were contaminated according to the following procedure: The 100 kg of vigin pellets were filled into 4 barrels (25 kg each). To each of the barrels, a mixture of 25 ml toluene, 25 ml, chlorobenzene, 25 ml limonene, 25 ml phenyl cyclohexane, 25 g benzophenone, 25 ml butyl salicylate, 25 g methyl palmitate, 25 g diethylhexyl adipate, 25 g tris(ethylhexyl) trimellitate and 25 g ethylhexyl triazone (Uvinul T150 dissolved in 25 ml ethyl acetate) was given. Subsequently the barrels were sealed and stored for 7 d at 50 °C. The sealed barrels were turned/rolled each day. Subsequently. After contamination the pellets were rinsed with 10% ethanol in order to remove contaminants from the surface of the pellets. The pellets were combined into 4 barrels and shipped to the customer.

4 Samples

The commissioning party made available the samples listed in Table 2.

Table 2: Description of the investigated samples

Sample	Sample description
Sample input 9	Input before decontamination trail 9
Sample output 9	output after decontamination trail 9
Sample input 13	Input before decontamination trail 13
Sample output 13	output after decontamination trail 13
Sample input 14	Input before decontamination trail 14
Sample output 14	output after decontamination trail 14
Sample input 23A	Input before decontamination trail 23A
Sample output 23A	output after decontamination trail 23A
Sample input 23B	Input before decontamination trail 23B
Sample output 23B	output after decontamination trail 23B

5 Extraction method

5.1 Quantification challenge test samples

In each case a 1.0 g sample was weighed into a headspace-vial and extracted with 10 ml dichloromethane for 3 d at 40°C. The extracts were then analyzed by gas chromatography. Gas chromatograph: Agilent 6890, column: ZB 1 MS - 20 m - 0.18 mm i.d. - 0.18 µm film thickness, temperature program: 50°C (2 min), heat at 5°C min^{-1} to 340°C (10 min), Split: 10 ml min^{-1}. The FID signals of

the model contaminants in the gas chromatogram were integrated. The concentrations of the respective contaminants were determined from calibration graphs obtained using external standards.

5.2 Quantification ethylhexyl triazone (Uvinul T150)

1.0 g of the polymer sample were extracted with 10.0 ml dichloromethane for 2 days at 40 °C. An aliquot of the dichloromethane extracts was evaporated to dryness under a stream of nitrogen. The residue was re-dissolved in the same amount of 95% ethanol. The ethanolic solutions were used for HPLC analysis: HPLC equipment: Column: Xbridge (150 x 3 mm, 5 µ; Phenomenex); eluent: 95% methanol to 100% methanol (gradient); mobile phase flow rate: 0.5 ml/min, column oven: 40 °C. Quantification was achieved by coupling the HPLC to a mass spectrometer (Thermo LTQ). For detection, the molecular mass of trimethylolpropane was selected in single reaction monitoring (SRM) mode and the characteristic daughter fragment was detected. The calibration was performed in dichloromethane handled like the samples. All analyses were performed in duplicate.

5.3 Detection limits

Table 3: Detection limits of the applied method for the surrogates

Surrogate	Detection limit [mg/kg, ppm]
Toluene	0.1
Chlorobenzene	0.1
Limonene	0.1
Phenyl cyclohexane	0.1
Butyl salicylate	0.2
Benzophenone	0.1
Methyl palmitate	0.1
Diethylhexyl adipate DEHA	0.2
Tris(ethylhexyl)trimellitate TEHTM	0.3
Ethylhexyl triazone (Uvinul T150)	1.0

5.4 Diffusion modelling

Diffusion modeling was applied to predict the migration from the recyclate containing food contact materials into food. Diffusion modelling was performed using the AKTS SML software version 4.54 (AKTS AG, Siders, Switzerland). The

program uses finite element analysis[1]. The modelling parameters used by EFSA are given in the modelling Guide of the European Joint Research Centre JCR[2]. In addition, the following conditions were used:

- Modelling parameters: $A_P' = 14.5$, $\tau = 1577$ K[2]
- polymer density: 0.95 g/cm^3
- over-estimative factor: 2[3]
- Food density: 1 kg/l
- Partition coefficient: K = 1 (good solubility

6 Results

The results of the quantification of the surrogates in the investigated challenge test samples are summarized in Table 4. Example gas chromatograms of the dichloromethane extracts are shown in Figure 1 to Figure 11.

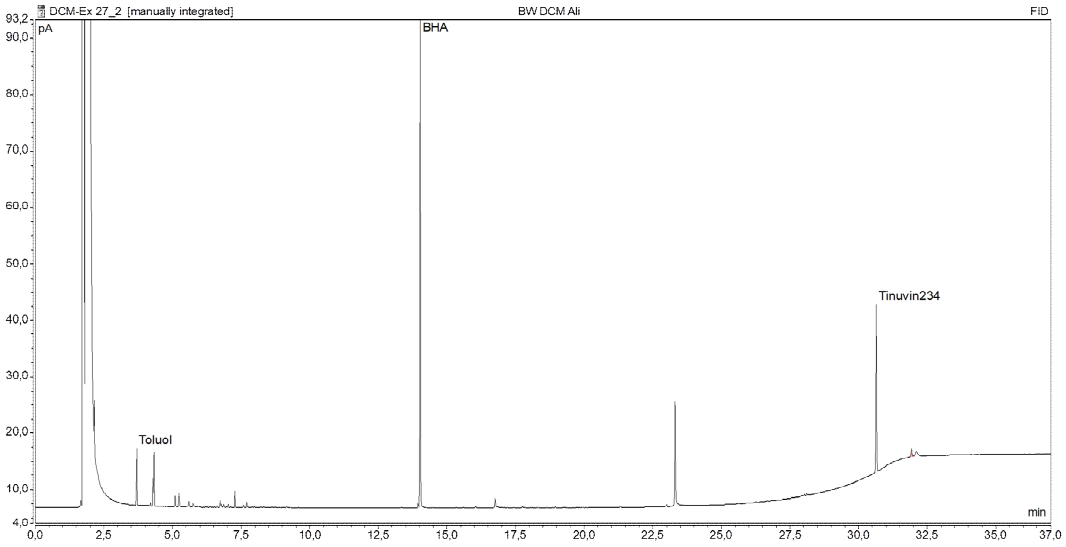


Figure 1: Gas chromatogram of the extract of solvent used for extraction (blind)

[1] Roduit, B.; Borgeat, C. H.; Cavin, S.; Fragniere, C.; Dudler, V. Application of finite element analysis (FEA) for the simulation of release of additives from multilayer polymeric packaging structures. Food Addit. Contam. Part A 2005, 22, 945–955.

[2] Practical guidelines on the application of migration modelling for the estimation of specific migration, EU Report 27529 EN, ISBN 978-92-79-52790-6, 2015. Available online: https://op.europa.eu/de/publication-detail/-/publication/1b79bc61-97f6-11e5-983e-01aa75ed71a1

[3] EFSA CEF Panel (EFSA Panel on Food Contact Materials, Enzymes, Flavourings and Processing Aids), Scientific Opinion on the safety assessment of the processes 'Biffa Polymers' and 'CLRrHDPE' used to recycle high-density polyethylene bottles for use as food contact material. EFSA J. 2015, 13, 4016. https://doi.org/10.2903/j.efsa.2015.4016.

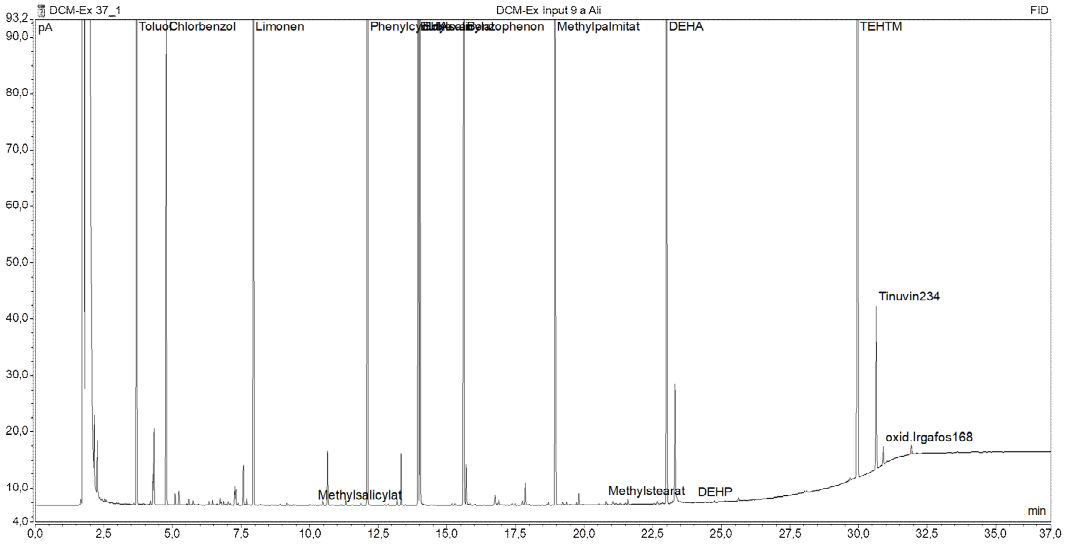


Figure 2: Gas chromatogram of the extract of sample input 9

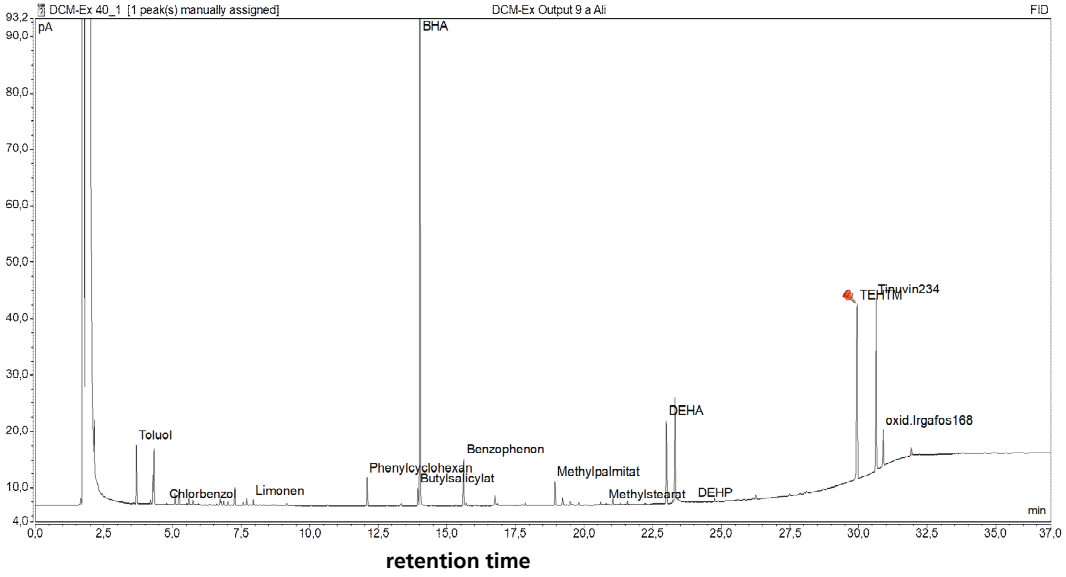


Figure 3: Gas chromatogram of the extract of sample output 9

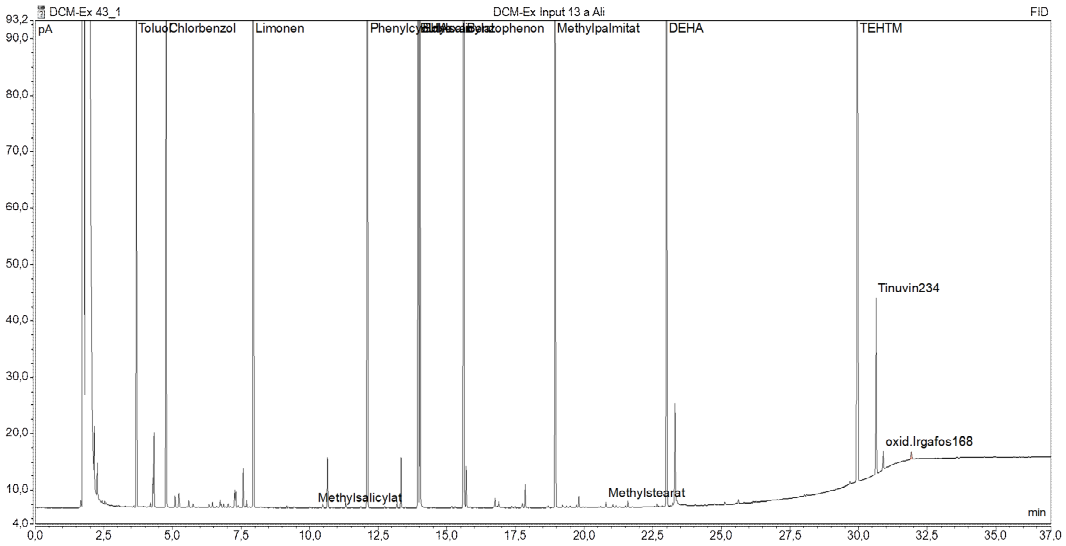


Figure 4: Gas chromatogram of the extract of sample input 13

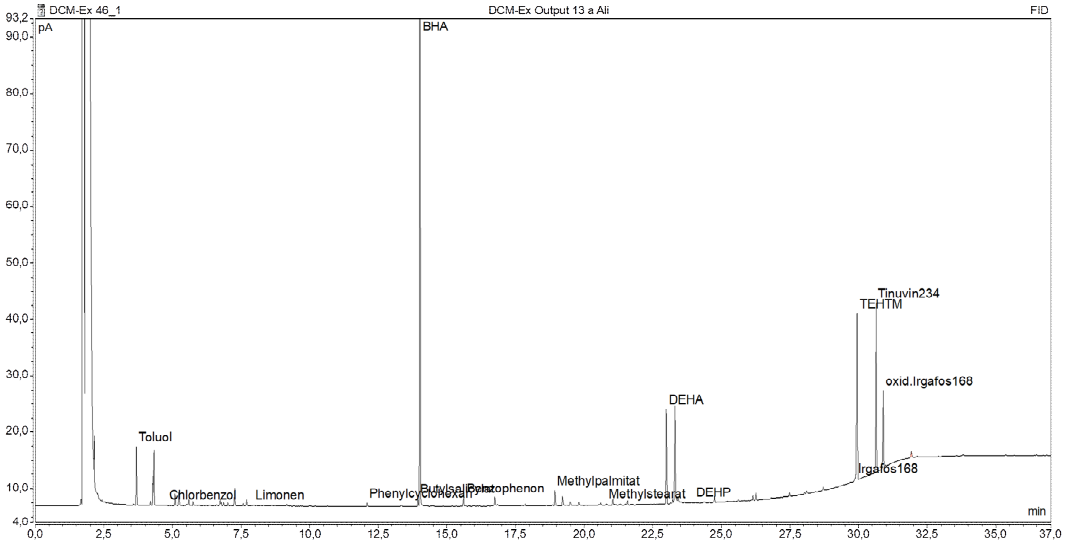
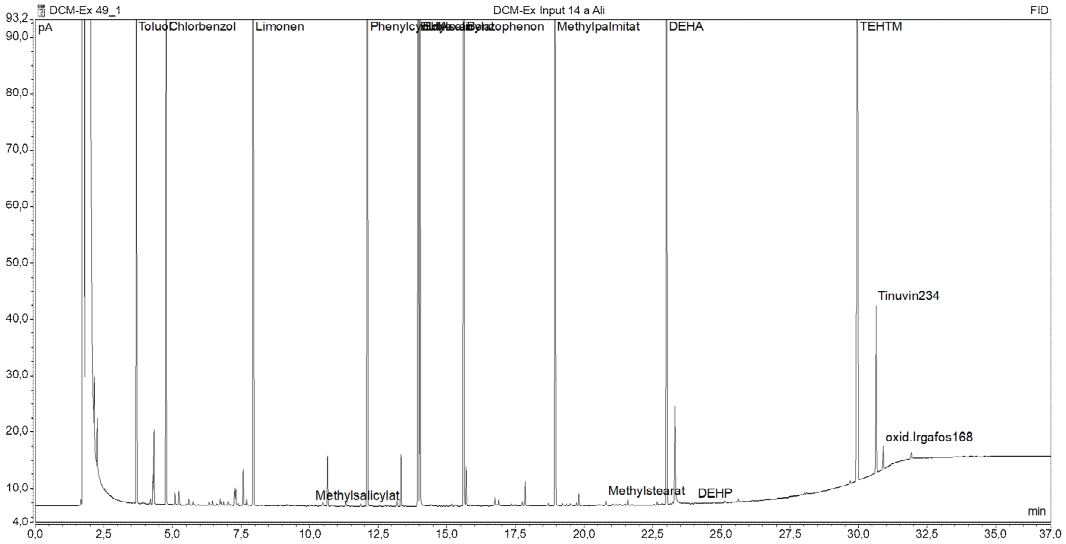
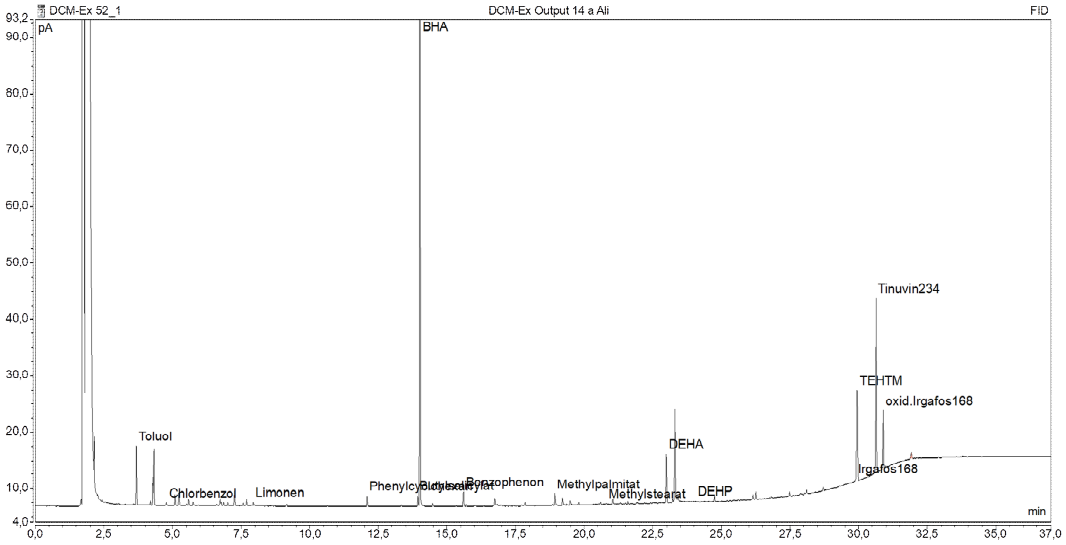


Figure 5: Gas chromatogram of the extract of sample output 13



retention time

Figure 6: Gas chromatogram of the extract of sample input 14



retention time

Figure 7: Gas chromatogram of the extract of sample output 14

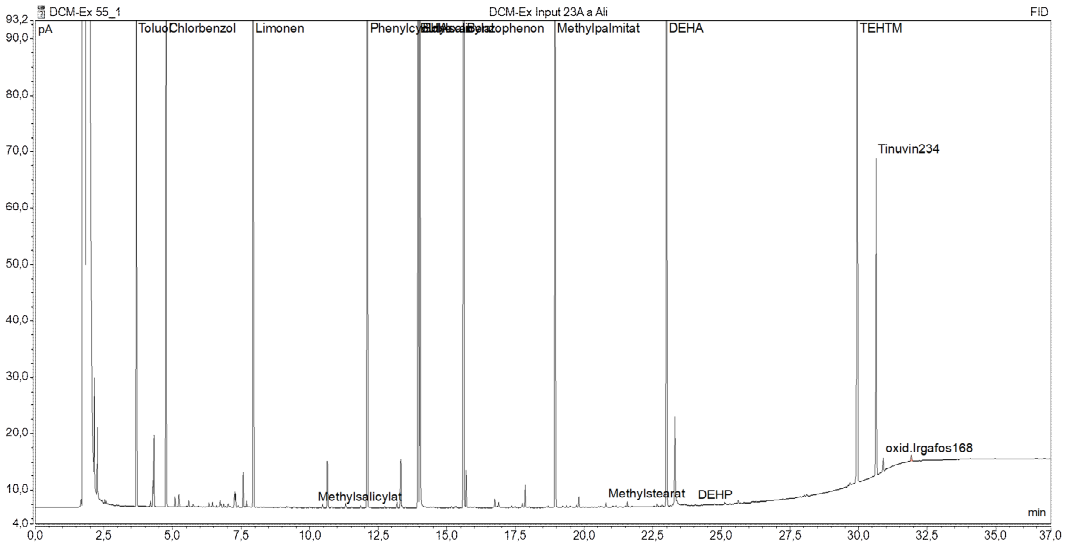


Figure 8: Gas chromatogram of the extract of sample input 23A

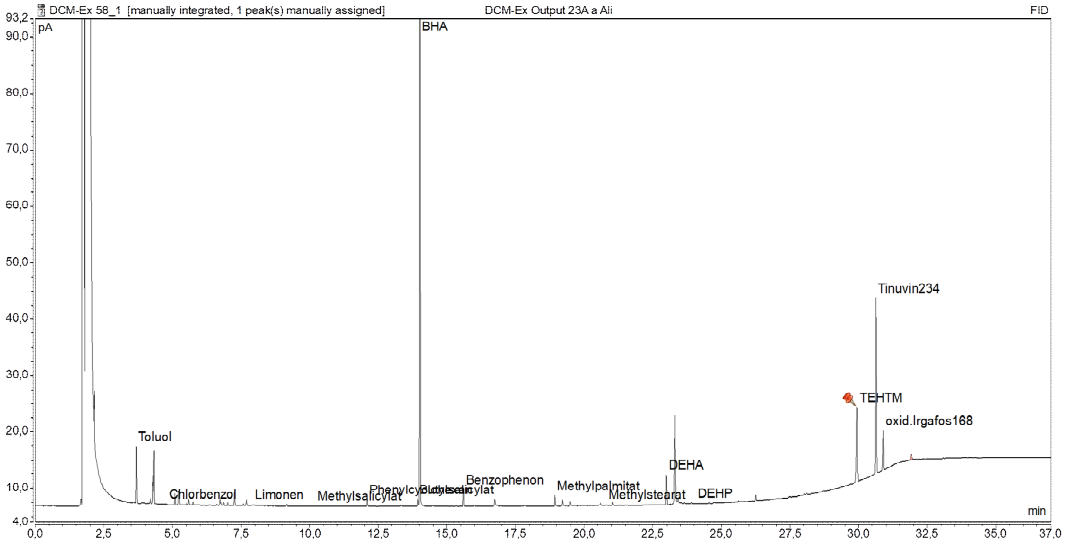


Figure 9: Gas chromatogram of the extract of sample output 23A

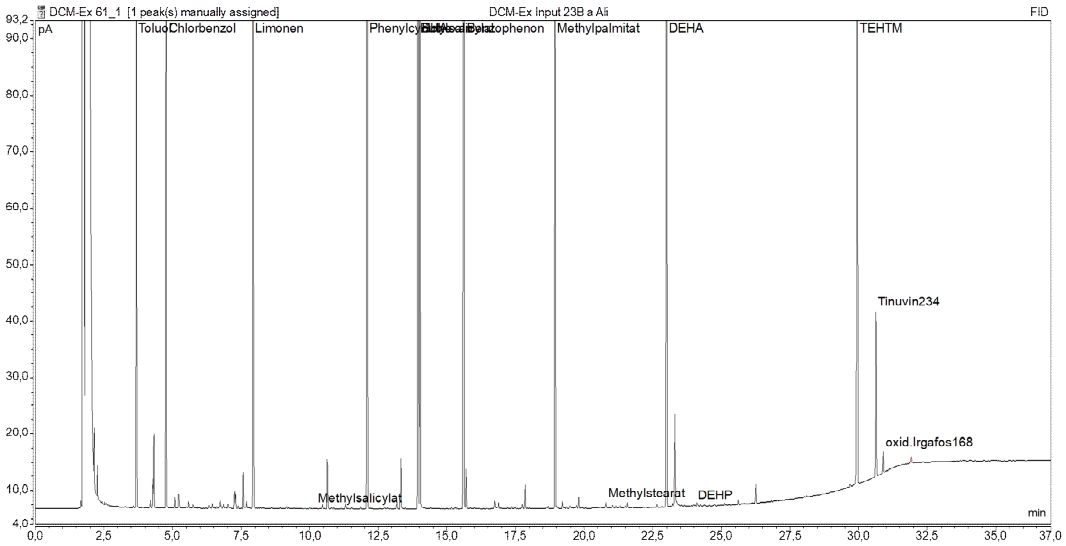


Figure 10: Gas chromatogram of the extract of sample input 23B

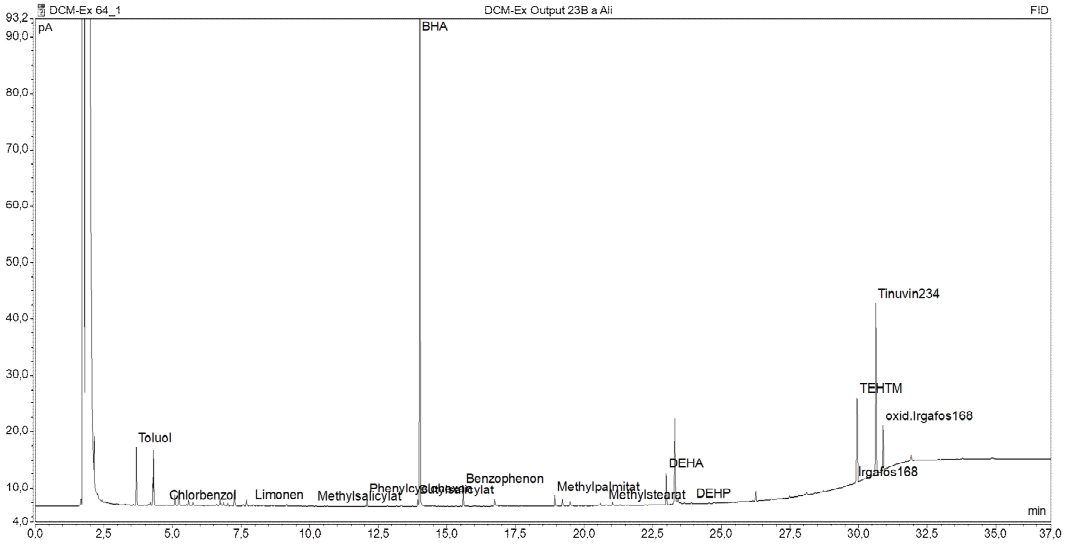


Figure 11: Gas chromatogram of the extract of sample output 23B

Table 4: Concentrations of the model contaminants in the HDPE material

Sample	Concentration [mg/kg, ppm] (cleaning efficiency)									
	Toluene	Chloro-benzene	Limonene	Phenyl cyclohexane	Butyl salicylate	Benzo-phenone	Methyl palmitate	DEHA	TEHTM	Uvinul T150
input 9a	376.7 ±1.0	557.5 ±1.7	674.2 ±2.4	753.9 ±1.1	850.4 ±0.3	872.5 ±1.5	642.1 ±0.4	596.6 ±1.8	671.7 ±3.5	1084.4
input 9b	361.1 ±0.7	536.0 ±1.2	654.1 ±2.4	737.9 ±4.1	837.1 ±6.1	860.3 ±6.7	668.6 ±5.9	598.0 ±6.6	656.7 ±3.9	895.3
input 9c	374.0 ±1.4	551.5 ±1.9	659.1 ±3.3	721.2 ±2.5	821.7 ±1.7	842.8 ±0.8	550.3 ±0.4	536.4 ±1.8	653.6 ±2.1	936.0
input 13a	350.9 ±1.9	532.9 ±2.2	657.5 ±1.0	742.8 ±1.1	839.2 ±1.6	863.4 ±1.5	662.2 ±0.5	609.3 ±1.2	686.4 ±0.8	919.4
input 13b	360.8 ±0.6	547.2 ±1.4	660.8 ±2.8	740.4 ±6.4	849.8 ±7.7	877.7 ±8.5	687.7 ±7.2	609.3 ±7.8	654.3 ±0.5	900.2
input 13c	349.7 ±2.0	532.0 ±2.8	639.4 ±2.9	718.5 ±1.6	823.3 ±4.5	850.0 ±7.0	613.5 ±5.8	571.6 ±6.7	634.7 ±9.8	936.2
input 14a	369.1 ±1.6	546.2 ±2.8	665.9 ±5.6	775.9 ±8.0	877.7 ±6.3	898.7 ±4.7	763.7 ±2.4	647.2.89 ±	767.0 ±9.3	967.0
input 14b	368.3 ±0.1	542.5 ±0.3	645.3 ±0.4	730.0 ±0.7	832.8 ±1.3	857.7 ±0.9	654.0 ±1.6	588.1 ±4.9	670.0 ±1.0	915.1
input 14c	366.5 ±0.5	541.4 ±0.3	662.2 ±0.6	761.7 ±0.3	862.1 ±0.8	886.1 ±2.1	747.7 ±2.2	681.6 ±2.6	721.8 ±0.6	1033.1
input 23Aa	361.4 ±0.2	520.2 ±0.3	597.5 ±0.4	684.2 ±0.2	794.7 ±1.3	826.5 ±2.5	619.8 ±3.1	541.6 ±2.0	599.2 ±2.6	831.5
input 23Ab	414.2 ±0.2	589.9 ±0.2	700.7 ±0.2	801.0 ±0.1	909.2 ±0.3	938.5 ±1.0	738.7 ±2.0	650.9 ±4.5	676.8 ±0.1	815.5
input 23Ac	385.1 ±1.5	552.7 ±2.3	637.1 ±2.5	727.3 ±1.0	838.4 ±2.1	873.4 ±6.4	655.9 ±6.5	576.6 ±7.3	623.5 ±1.8	894.8

Sample	Concentration [mg/kg, ppm] (cleaning efficiency)									
	Toluene	Chloro-benzene	Limonene	Phenyl cyclohexane	Butyl salicylate	Benzo-phenone	Methyl palmitate	DEHA	TEHTM	Uvinul T150
input 23Ba	323.8 ±0.7	499.4 ±0.9	622.1 ±1.3	708.4 ±0.3	816.2 ±2.4	847.1 ±6.5	652.1 ±5.5	606.3 ±9.1	639.5 ±1.1	899.4
input 23Bb	323.5 ±0.9	497.8 ±1.1	623.1 ±1.3	703.8 ±0.4	820.4 ±0.1	851.9 ±0.1	619.7 ±1.6	584.0 ±0.1	633.2 ±2.5	860.3
input 23Bc	319.9 ±0.3	493.2 ±0.8	622.5 ±1.7	716.2 ±3.3	823.6 ±4.6	851.1 ±5.5	628.5 ±4.6	574.5 ±4.2	629.5 ±1.8	911.6
mean input	**360.3 ±0.6**	**536.0 ±0.9**	**648.1 ±1.4**	**734.9 ±2.4**	**839.7 ±2.6**	**866.5 ±2.8**	**660.3 ±2.4**	**598.2 ±2.7**	**661.2 ±3.0**	**920.0 ±69.2**
output 9a	1.4 ±0.3	0.9 ±0.2	4.0 ±0.3	14.7 ±0.1	11.1 ±0.1	27.4 ±0.2	14.8 ±0.1	58.2 ±0.5	180.7 ±0.5	97.1
output 9b	1.4 ±0.1	0.8 ±0.1	3.6 ±0.1	14.1 ±0.1	10.6 ±0.1	25.4 ±0.4	13.9 ±0.1	56.9 ±0.1	177.1 ±1.1	90.3
output 9c	1.1 ±0.3	0.9 ±0.2	4.0 ±0.3	14.1 ±0.1	10.5 ±0.1	25.8 ±0.1	13.7 ±0.1	55.1 ±0.3	172.8 ±0.1	87.7
mean output 9	**1.3 ±0.2 (99.6%)**	**0.8 ±0.1 (99.9%)**	**3.9 ±0.2 (99.4%)**	**14.3 ±0.3 (98.1%)**	**10.7 ±0.4 (98.7%)**	**26.2 ±1.1 (97.0%)**	**14.1 ±0.6 (97.9%)**	**56.7 ±1.6 (90.5%)**	**176.9 ±4.0 (73.2%)**	**91.7 ±4.9 (90.0%)**
output 13a	1.3 ±0.3	0.3 ±0.1	0.4 ±0.1	2.3 ±0.1	3.6 ±0.6	6.4 ±0.1	10.1 ±0.1	62.9 ±0.3	164.9 ±0.5	53.1
output 13b	1.1 ±0.3	0.1 ±0.2	0.4 ±0.1	2.2 ±0.1	4.1 ±0.1	5.9 ±0.1	9.6 ±0.1	62.7 ±0.5	180.1 ±0.2	56.6
output 13c	0.8 ±0.4	<0.1	<0.1	2.2 ±0.1	4.1 ±0.1	5.8 ±0.1	9.5 ±0.1	60.0 ±0.1	153.6 ±0.1	45.0
mean output 13	**1.1 ±0.2 (99.7%)**	**0.2 ±0.1 (99.9%)**	**0.2 ±0.2 (99.9%)**	**2.2 ±0.1 (99.7%)**	**3.9 ±0.3 (99.5%)**	**6.0 ±0.3 (99.3%)**	**9.7 ±0.4 (98.5%)**	**61.9 ±1.7 (89.7%)**	**166.2 ±13.3 (74.9%)**	**51.6 ±6.0 (94.4%)**

Sample	Concentration [mg/kg, ppm] (cleaning efficiency)									
	Toluene	Chloro-benzene	Limonene	Phenyl cyclohexane	Butyl salicylate	Benzo-phenone	Methyl palmitate	DEHA	TEHTM	Uvinul T150
output 14a	2.2 ±0.1	2.8 ±0.1	2.9 ±0.1	6.7 ±0.1	8.9 ±0.2	10.7 ±0.4	8.4 ±0.1	35.4 ±0.6	85.8 ±0.1	41.7
output 14b	0.5 ±0.4	2.9 ±0.2	2.4 ±0.6	6.9 ±0.1	8.9 ±0.2	10.5 ±0.1	8.4 ±0.1	38.0 ±0.3	90.7 ±4.2	40.5
output 14c	0.8 ±0.1	3.1 ±0.1	2.7 ±0.7	7.5 ±0.1	9.5 ±0.2	11.0 ±0.1	8.9 ±0.1	40.5 ±0.1	101.4 ±0.2	46.9
mean output 14	**1.1 ±0.9 (99.7%)**	**2.9 ±0.1 (99.5%)**	**2.7 ±0.3 (99.6%)**	**7.0 ±0.4 (99.0%)**	**9.1 ±0.3 (98.9%)**	**10.7 ±0.2 (98.8%)**	**8.5 ±0.3 (98.7%)**	**38.0 ±2.6 (93.6%)**	**92.6 ±8.0 (86.0%)**	**43.0 ±3.4 (95.3%)**
output 23Aa	0.4 ±0.1	0.5 ±0.1	0.7 ±0.1	4.3 ±0.1	3.9 ±0.2	11.0 ±0.2	6.5 ±0.1	20.5 ±0.4	71.0 ±0.4	74.6
output 23Ab	0.5 ±0.1	0.5 ±0.1	0.8 ±0.1	4.8 ±0.1	4.1 ±0.1	11.0 ±0.5	6.2 ±0.1	19.3 ±0.2	61.8 ±0.4	77.3
output 23Ac	0.4 ±0.1	0.6 ±0.2	0.9 ±0.1	5.0 ±0.1	4.4 ±0.1	11.7 ±0.1	5.9 ±0.1	17.9 ±0.2	55.4 ±0.2	71.8
mean output 23A	**0.4 ±0.1 (99.9%)**	**0.6 ±0.1 (99.9%)**	**0.8 ±0.1 (99.9%)**	**4.7 ±0.4 (99.4%)**	**4.1 ±0.2 (99.5%)**	**11.2 ±0.4 (98.7%)**	**6.2 ±0.3 (99.1%)**	**19.2 ±1.3 (89.5%)**	**62.7 ±7.8 (90.5%)**	**74.6 ±2.8 (91.9%)**
output 23Ba	0.5 ±0.1	0.5 ±0.1	0.8 ±0.1	5.1 ±0.1	4.4 ±0.1	12.1 ±0.2	6.5 ±0.1	20.8 ±0.4	74.5 ±0.6	87.6
output 23Bb	0.3 ±0.1	<0.1	0.7 ±0.1	4.7 ±0.1	4.1 ±0.1	11.7 ±0.1	7.4 ±0.1	23.4 ±0.3	91.3 ±0.7	106.7
output 23Bc	<0.1	0.3 ±0.1	0.8 ±0.1	4.9 ±0.1	4.1 ±0.1	11.0 ±0.1	6.6 ±0.2	22.2 ±0.1	76.8 ±0.2	104.4
mean output 23B	**0.3 ±0.2 (99.9%)**	**0.3 ±0.2 (99.9%)**	**0.8 ±0.1 (99.9%)**	**4.9 ±0.2 (99.3%)**	**4.2 ±0.2 (99.5%)**	**11.6 ±0.6 (98.7%)**	**6.8 ±0.5 (99.0%)**	**22.1 ±1.3 (96.3%)**	**80.9 ±9.1 (87.8%)**	**99.6 ±10.4 (89.2%)**

7 Food law compliance evaluation

Diffusion models provide a scientific tool for establishing a correlation between the migration into contact media and the corresponding concentration $C_{P,0}$ of a migrant (surrogates) in the HDPE closures or pellets as the final product of the super-clean recycling process. In this way maximum surrogate concentrations in HDPE can be established which would not lead to exceeding a certain migration value of interest.

7.1 Milk bottles

According to the EFSA Scientific opinion on HDPE milk bottles[4], the maximum migration of compounds from the post-consumer materials should be below of 0.06 µg/kg for a toddler. In addition, the EFSA has defined the maximum contamination level in post-consumer HDPE recyclates to 0.5 mg/kg. Using migration models, the maximum amount of substances of different molecular weights can be calculated using $A_P' = 14.5$ and $\tau = 1577$ K. The maximum concentrations C_{mod} of the applied surrogates were calculated for a food package with 1 l volume and 600 cm^2 (EU cube). This maximum concentration corresponds to the assumed EFSA migration limit of 0.06 µg/kg in food for milk bottles. The calculation was done for a food with high solubility for the surrogates (partition coefficient $K_{Polymer/Food} = 1$) at conditions of 15 d at 5 °C. These modelling conditions and used by EFSA in the evaluation of HDPE milk bottles[4]. The results are visualized in Figure 12 for the final product (sample output 14).

Based on the challenge test results a recyclate content of 83.2% is possible.

[4]Scientific Opinion on the safety assessment of the processes 'Biffa Polymers' and 'CLRrHDPE' used to recycle high-density polyethylene bottles for use as food contact material, EFSA Journal 2015;13(2):4016 (25 pages)

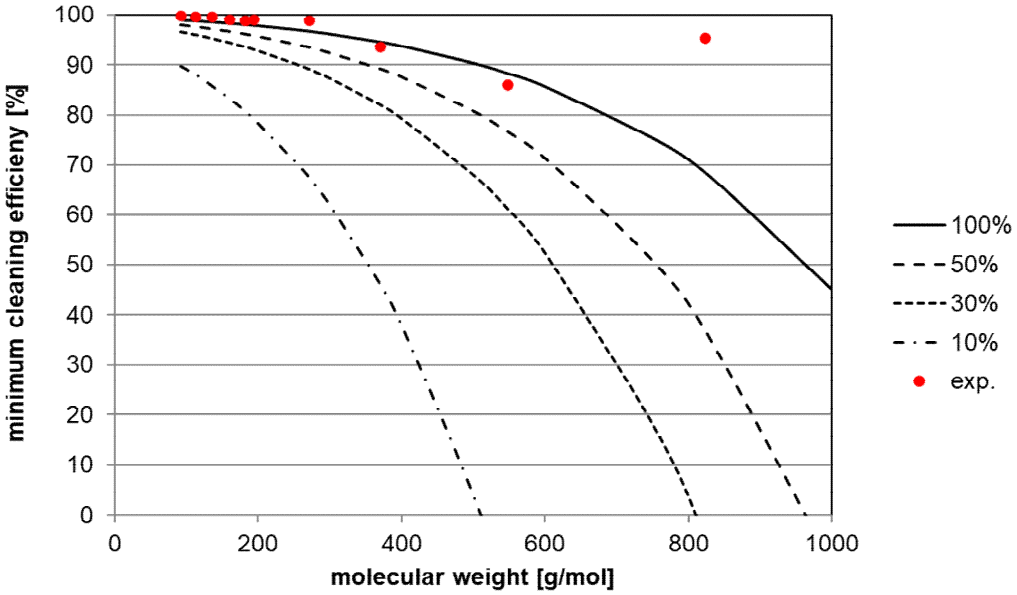


Figure 12: Cleaning efficiencies of surrogates in the challenge test (sample output 14) for the EFSA scenario for milk bottles[4] (initial contamination level **0.5 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

7.2 Closures for mineral water bottles

Evaluation criteria for mineral water closures with post-consumer recyclates are not published till now. However, two EFSA publications on the evaluation criteria for PET mineral water bottles and HDPE milk bottles can be applied in order to evaluate the HDPE mineral water closures. It should be noted here that EFSA might evaluate the recyclate containing closures for mineral water in a different way.

According to the EFSA Scientific opinion on HDPE milk bottles[4] and the (new) EFSA criteria published for PET mineral water bottles[5], the maximum migration of compounds from the post-consumer materials should be below of 0.019 µg/kg (1300 ml consumption of mineral water for an infant with 5 kg bw). This exposure scenario is applied by EFSA for infants and for mineral water. Using migration models, the maximum concentration of substances of different molecular weights can be calculated using $A_P' = 14.5$ and $\tau = 1577$ K. The maximum concentrations C_{mod} of the applied surrogates were calculated for a food package with 1 l volume bottle and with an inner surface area of the closure of 3.2 cm^2 (data provided by the customer). The thickness of the closure was assumed to 1250 µm. This maximum concentration corresponds to the assumed migration limit of 0.019 µg/kg in food. The calculation was done for a food with high solubility for the surrogates (partition coefficient $K_{Polymer/Food} = 1$) at

[5] Scientific Guidance on the criteria for the evaluation and on the preparation of applications for the safety assessment of post-consumer mechanical PET recycling processes intended to be used for manufacture of materials and articles in contact with food, EFSA Journal 2024, 22, 8879

conditions of 365 d at 25 °C with initial contamination levels of 3 mg/kg (similar to PET), 1 mg/kg and 0.5 mg/kg[6]. The results are given in Figure 13 to Figure 15.

Based on the challenge test results a recyclate content of 100% (initial contamination level 0.5 mg/kg and 1 mg/kg) and 39.0% (initial contamination level 3.0 mg/kg) is possible.

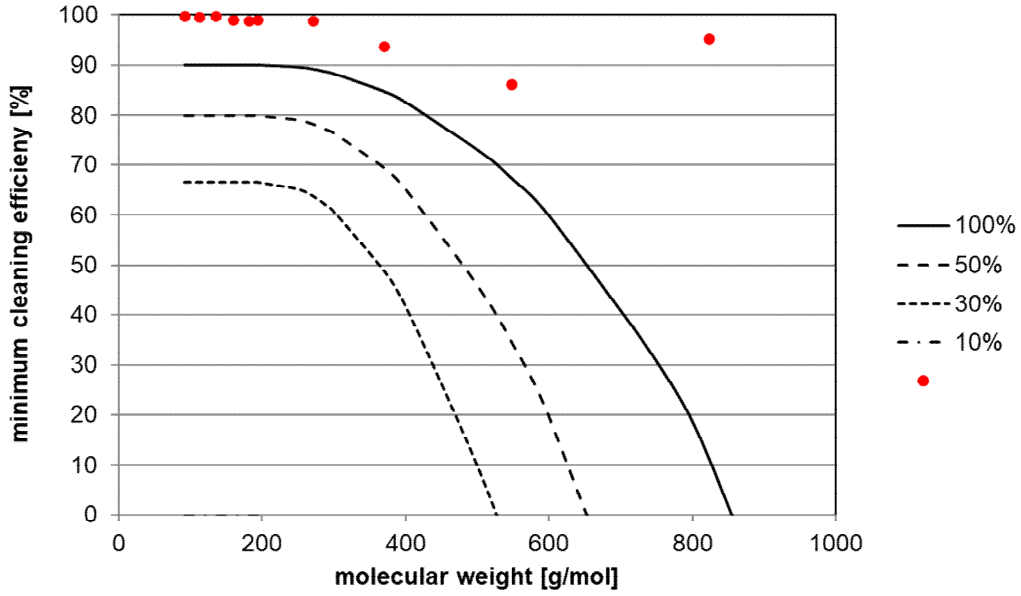


Figure 13: Cleaning efficiencies of surrogates in the challenge test (sample output 14), closures for mineral water bottles, initial contamination level **0.5 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

[6] F. Welle, Recycling of post-consumer HDPE bottle caps into new caps for food contact, Recycling, 2025, 10(6), 197; https://doi.org/10.3390/recycling10060197

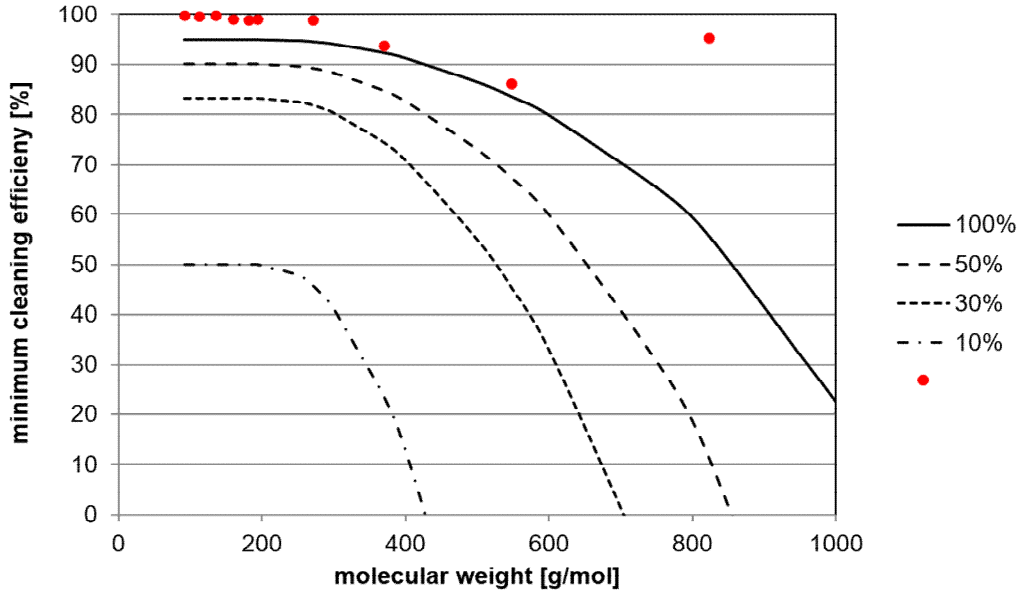


Figure 14: Cleaning efficiencies of surrogates in the challenge test (sample output 14), closures for mineral water bottles, initial contamination level **1 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

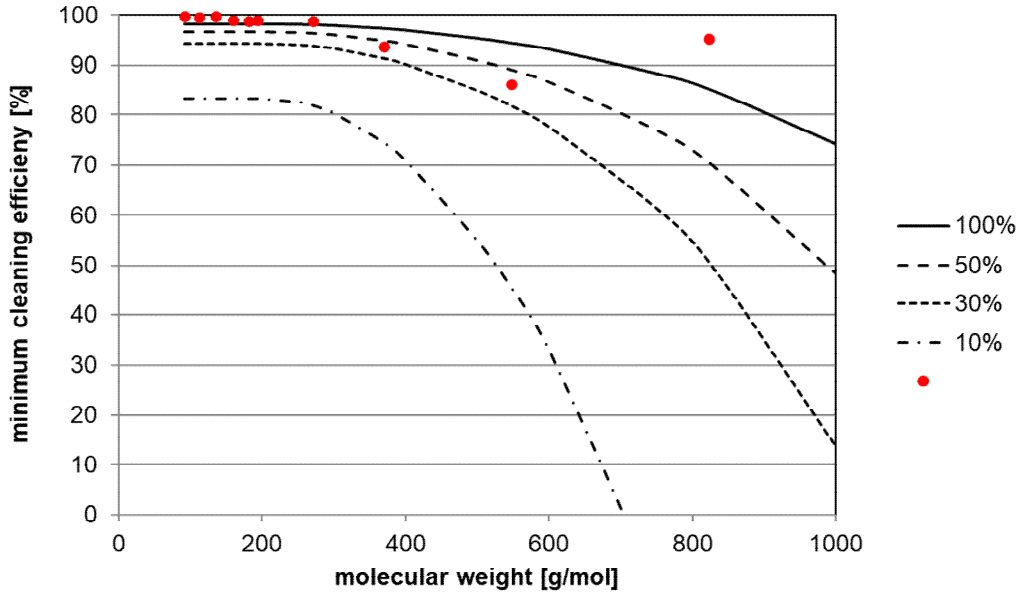


Figure 15: Cleaning efficiencies of surrogates in the challenge test (sample output 14), closures for mineral water bottles, initial contamination level **3 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

7.3 Closures for softdrink bottles

Evaluation criteria for softdink closures with post-consumer recyclates are not published till now. However, two EFSA publications on the evaluation criteria for PET mineral water bottles and HDPE milk bottles can be applied in order to evaluate the HDPE closures for softdrink bottles. It should be noted here that

EFSA might evaluate the recyclate containing closures for softdrink bottles in a different way.

According to the EFSA Scientific opinion on HDPE milk bottles[4] and the (new) EFSA criteria published for PET mineral water bottles[5], the maximum migration of compounds from the post-consumer materials should be below of 0.0626 µg/kg (960 ml consumption of softdrink for a toddler with 12 kg bw). Using migration models, the maximum concentration of substances of different molecular weights can be calculated using $A_P' = 14.5$ and $\tau = 1577$ K. The maximum concentrations C_{mod} of the applied surrogates were calculated for a food package with 1 l volume bottle and with an inner surface area of the closure of 3.2 cm^2 (data provided by the customer). The thickness of the closure was assumed to 1250 µm. This maximum concentration corresponds to the assumed migration limit of 0.0626 µg/kg in food. The calculation was done for a food with high solubility for the surrogates (partition coefficient $K_{Polymer/Food} = 1$) at conditions of 365 d at 25 °C with initial contamination levels of 3 mg/kg (similar for PET), 1 mg/kg and 0.5 mg/kg[6]. The results are given in Figure 16 to Figure 18.

Based on the challenge test results a recyclate content of 100% (initial contamination levels of 0.5 mg/kg, 1 mg/kg and 3.0 mg/kg) is possible.

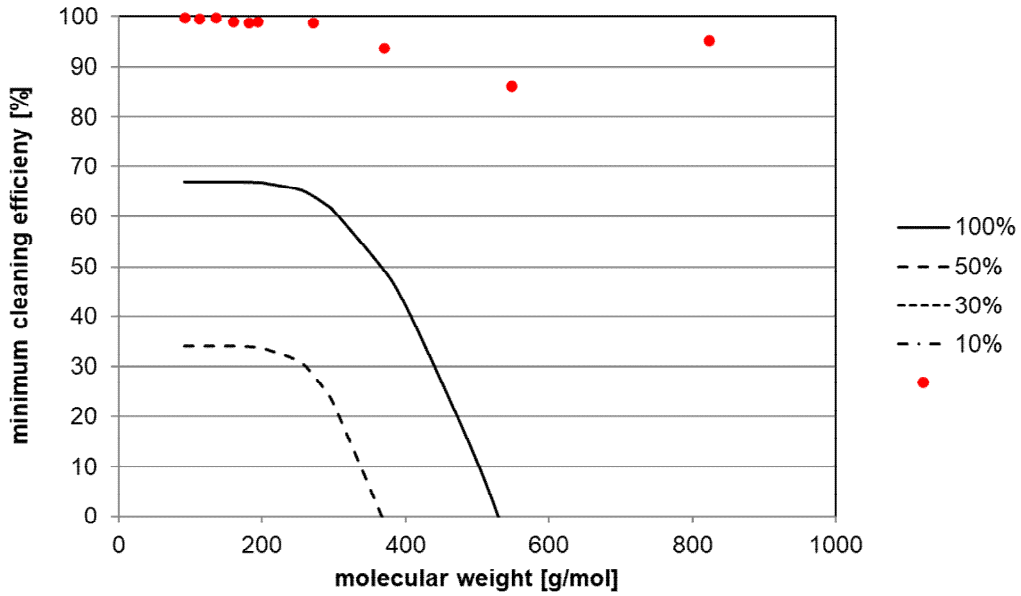


Figure 16: Cleaning efficiencies of surrogates in the challenge test (sample output 14), closures for softdrink bottles, initial contamination level **0.5 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

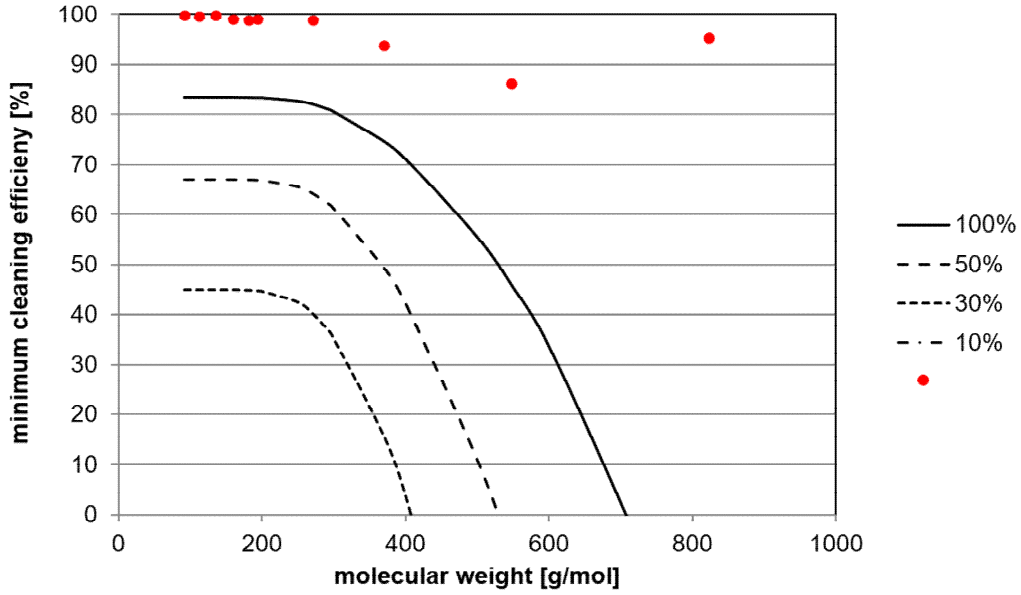


Figure 17: Cleaning efficiencies of surrogates in the challenge test (sample output 14), closures for softdrink bottles, initial contamination level **1 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

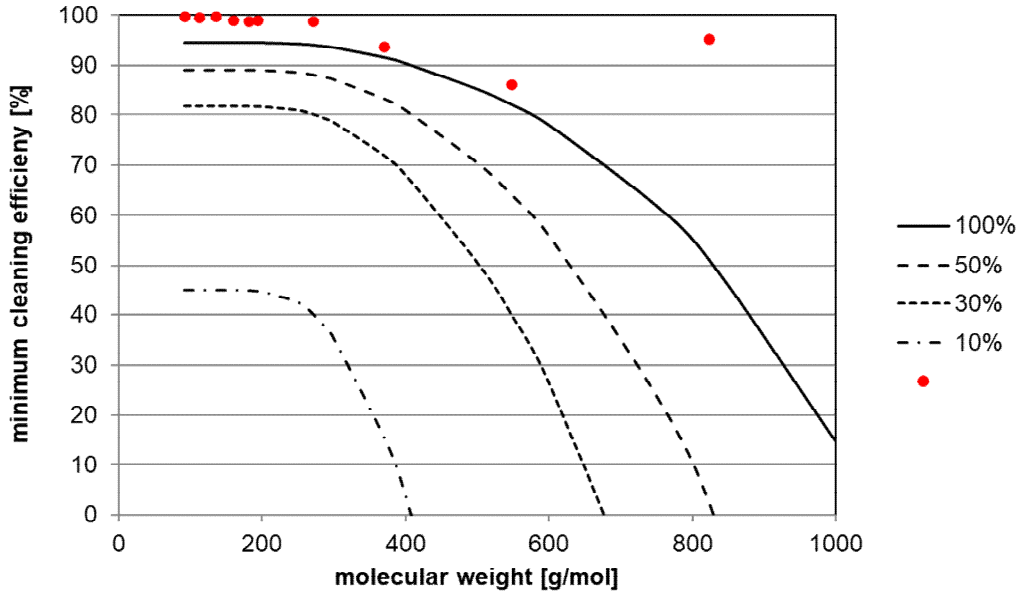


Figure 18: Cleaning efficiencies of surrogates in the challenge test (sample output 14), closures for softdrink bottles, initial contamination level **3 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

7.4 Packaging for solid and liquid food, 40 days at 6 °C (960 ml)

Evaluation criteria for packaging for solid and liquid food with post-consumer recyclates are not published till now. However, two EFSA publications on the evaluation criteria for PET mineral water bottles and HDPE milk bottles can be applied in order to evaluate the HDPE mineral water closures. It should be noted

here that EFSA might evaluate the recyclate containing packaging in a different way.

According to the EFSA Scientific opinion on HDPE milk bottles[4] and the (new) EFSA criteria published for PET mineral water bottles[5], the maximum migration of compounds from the post-consumer materials should be below of 0.0626 µg/kg (960 ml consumption of food for a toddler with 12 kg bw). Using migration models, the maximum concentration of substances of different molecular weights can be calculated using $A_P' = 14.5$ and $\tau = 1577$ K. The maximum concentrations C_{mod} of the applied surrogates were calculated for a food package with 1 l volume package and with an inner surface area of 6 dm^2. The thickness of the packaging was assumed to 300 µm. This maximum concentration corresponds to the assumed migration limit of 0.0626 µg/kg in food. The calculation was done for a food with high solubility for the surrogates (partition coefficient $K_{Polymer/Food} = 1$) at conditions of 40 days at 6 °C with initial contamination levels of 3 mg/kg (similar for PET), 1 mg/kg and 0.5 mg/kg[6]. The results are given in Figure 19 to Figure 21.

Based on the challenge test results a recyclate content of 49.2% (initial contamination level 0.5 mg/kg), 24.6% (initial contamination level 1 mg/kg) and 8.2% (initial contamination level 3.0 mg/kg) is possible.

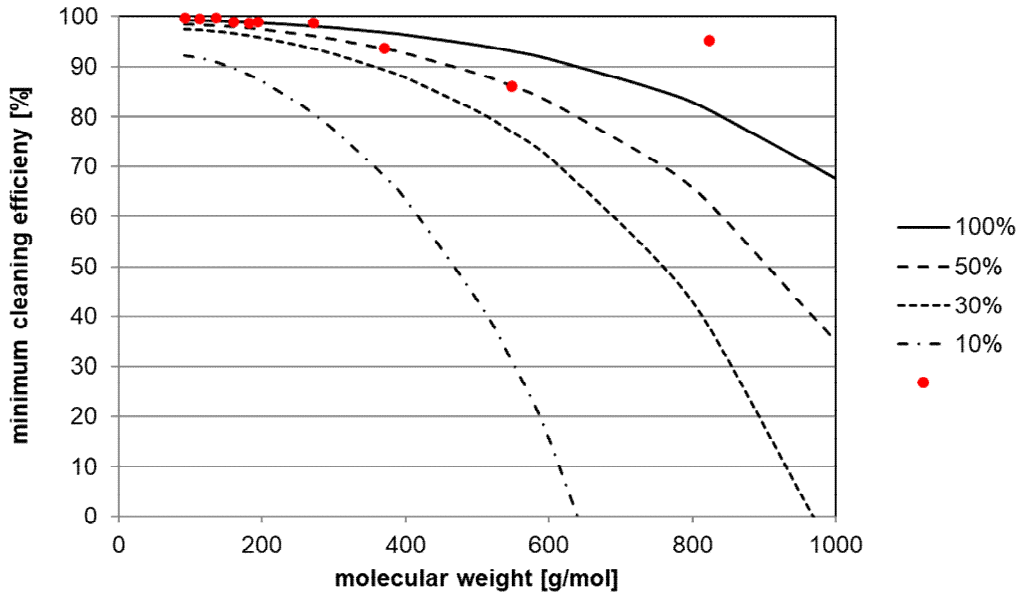


Figure 19: Cleaning efficiencies of surrogates in the challenge test (sample output 14), packaging for solid and liquid food, 40 days at 6 °C with 960 ml food consumption, initial contamination level **0.5 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

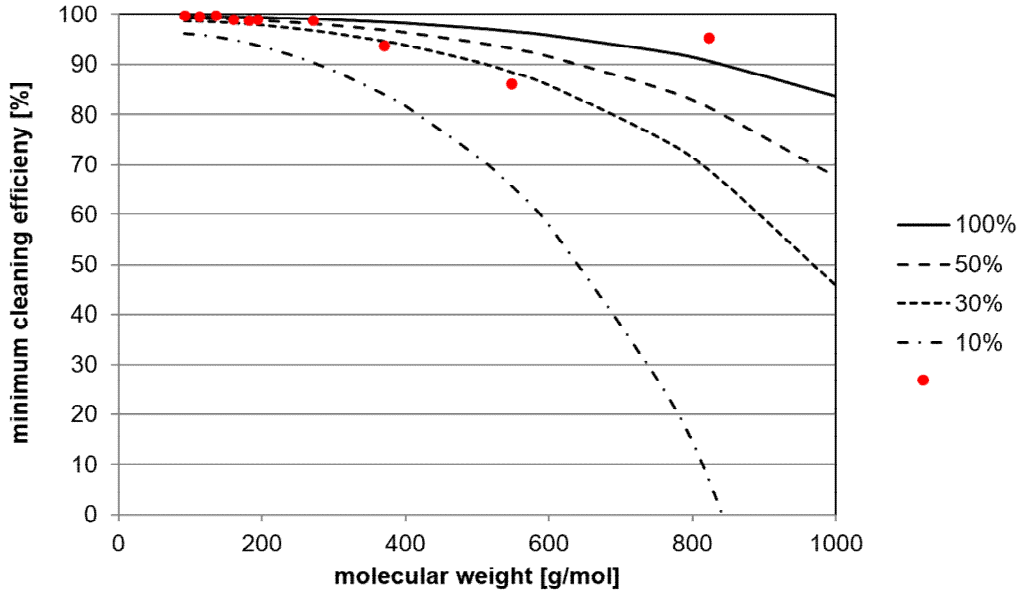


Figure 20: Cleaning efficiencies of surrogates in the challenge test (sample output 14), packaging for solid and liquid food, 40 days at 6 °C, with 960 ml food consumption, initial contamination level **1 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

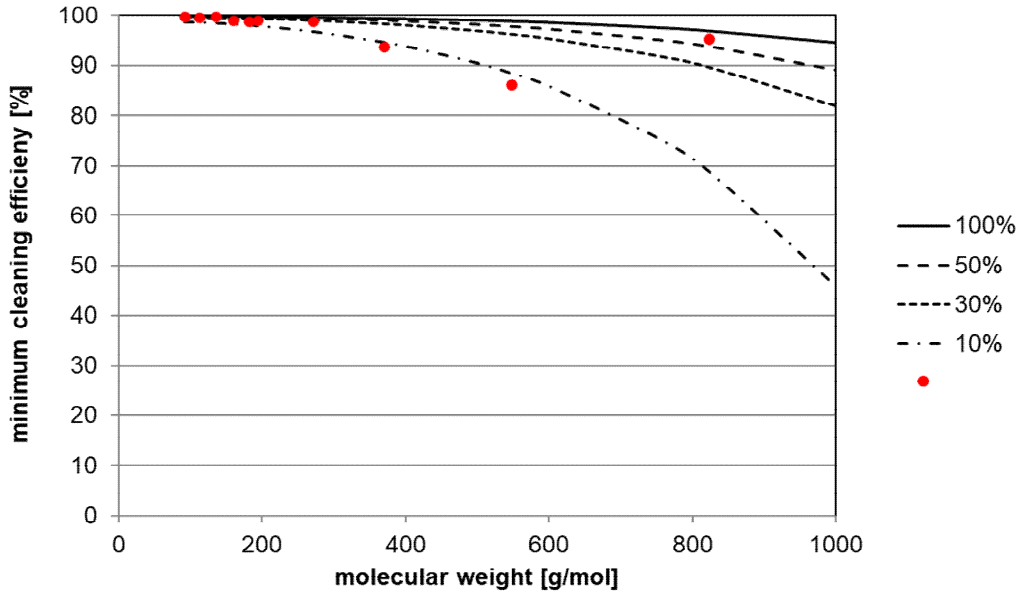


Figure 21: Cleaning efficiencies of surrogates in the challenge test (sample output 14), packaging for solid and liquid food, 40 days at 6 °C, with 960 ml food consumption, initial contamination level **3 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

7.5 Packaging for solid and liquid food, 40 days at 6 °C (350 ml)

The EFSA's food consumption is very high, which consequently limits the potential use of recycled materials in direct contact with food. At the client's

request, lower food consumption figures were therefore also calculated. When using 350 ml food consumption instead of 960 ml, the maximum migration of compounds from the post-consumer materials should be below of 0.171 µg/kg. Using migration models, the maximum concentration of substances of different molecular weights can be calculated using $A_P' = 14.5$ and $\tau = 1577$ K. The maximum concentrations C_{mod} of the applied surrogates were calculated for a food package with 1 l volume package and with an inner surface area of 6 dm^2. The thickness of the packaging was assumed to 300 µm. This maximum concentration corresponds to the assumed migration limit of 0.171 µg/kg in food. The calculation was done for a food with high solubility for the surrogates (partition coefficient $K_{Polymer/Food} = 1$) at conditions of 40 days at 6 °C with initial contamination levels of 3 mg/kg (similar for PET), 1 mg/kg and 0.5 mg/kg[6]. The results are given in Figure 22 to Figure 24.

Based on the challenge test results a recyclate content of 100% (initial contamination level 0.5 mg/kg), 67.3% (initial contamination level 1 mg/kg) and 22.4% (initial contamination level 3.0 mg/kg) is possible.

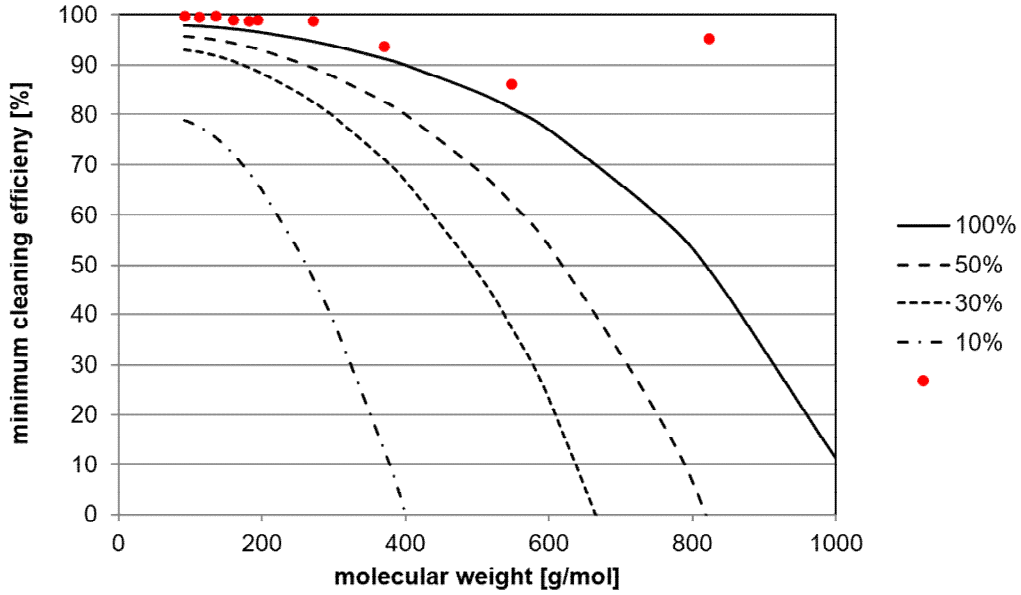


Figure 22: Cleaning efficiencies of surrogates in the challenge test (sample output 14), packaging for solid and liquid food, 40 days at 6 °C with 350 ml food consumption, initial contamination level **0.5 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

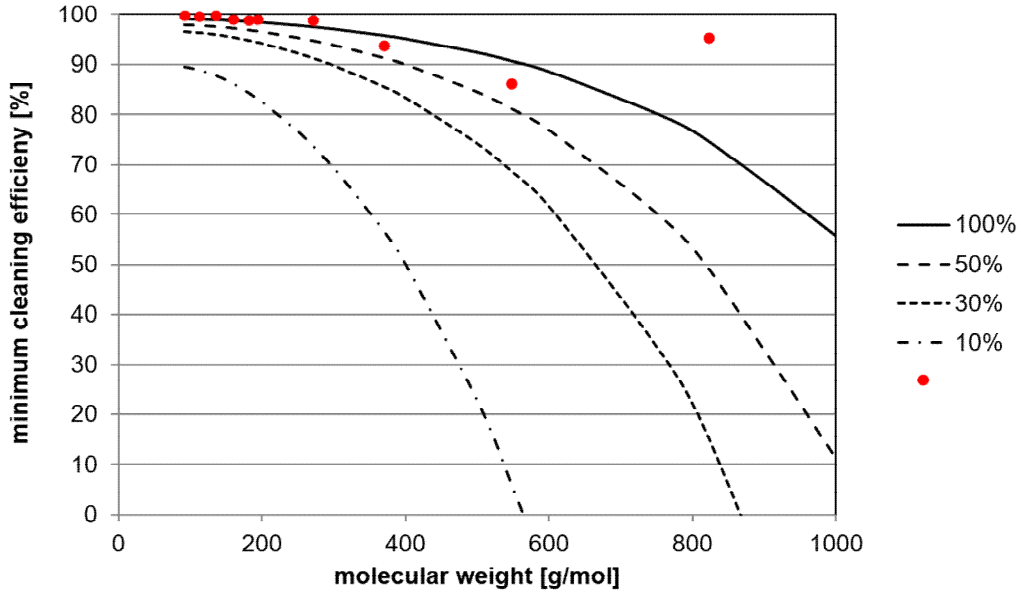


Figure 23: Cleaning efficiencies of surrogates in the challenge test (sample output 14), packaging for solid and liquid food, 40 days at 6 °C, with 350 ml food consumption, initial contamination level **1 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

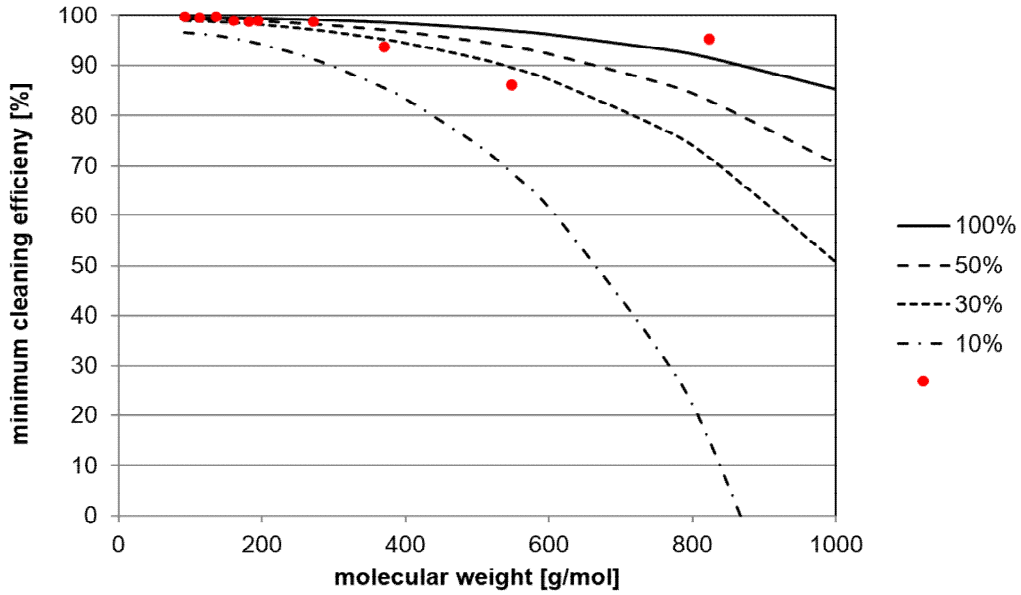


Figure 24: Cleaning efficiencies of surrogates in the challenge test (sample output 14), packaging for solid and liquid food, 40 days at 6 °C, with 350 ml food consumption, initial contamination level **3 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

7.6 Packaging for solid and liquid food, 40 days at 6 °C (250 ml)

The EFSA's food consumption is very high, which consequently limits the potential use of recycled materials in direct contact with food. At the client's

request, lower food consumption figures were therefore also calculated. When using 250 ml food consumption instead of 960 ml, the maximum migration of compounds from the post-consumer materials should be below of 0.240 µg/kg. Using migration models, the maximum concentration of substances of different molecular weights can be calculated using $A_P' = 14.5$ and $\tau = 1577$ K. The maximum concentrations C_{mod} of the applied surrogates were calculated for a food package with 1 l volume package and with an inner surface area of 6 dm^2. The thickness of the packaging was assumed to 300 µm. This maximum concentration corresponds to the assumed migration limit of 0.240 µg/kg in food. The calculation was done for a food with high solubility for the surrogates (partition coefficient $K_{Polymer/Food} = 1$) at conditions of 40 days at 6 °C with initial contamination levels of 3 mg/kg (similar for PET), 1 mg/kg and 0.5 mg/kg[6]. The results are given in Figure 25 to Figure 27.

Based on the challenge test results a recyclate content of 100% (initial contamination level 0.5 mg/kg), 94.4% (initial contamination level 1 mg/kg) and 31.5% (initial contamination level 3.0 mg/kg) is possible.

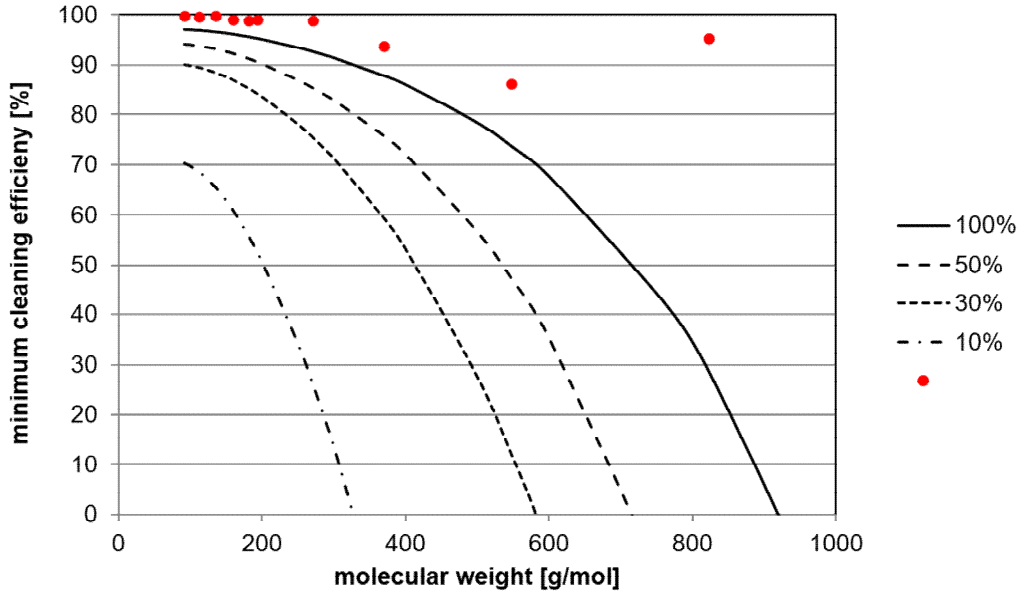


Figure 25: Cleaning efficiencies of surrogates in the challenge test (sample output 14), packaging for solid and liquid food, 40 days at 6 °C with 250 ml food consumption, initial contamination level **0.5 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

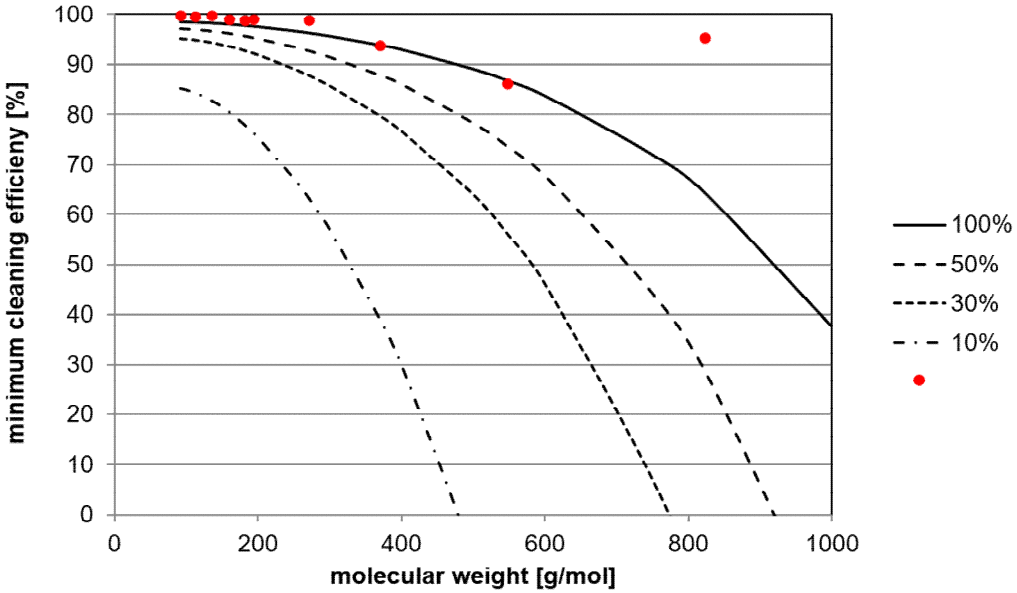


Figure 26: Cleaning efficiencies of surrogates in the challenge test (sample output 14), packaging for solid and liquid food, 40 days at 6 °C, with 250 ml food consumption, initial contamination level **1 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

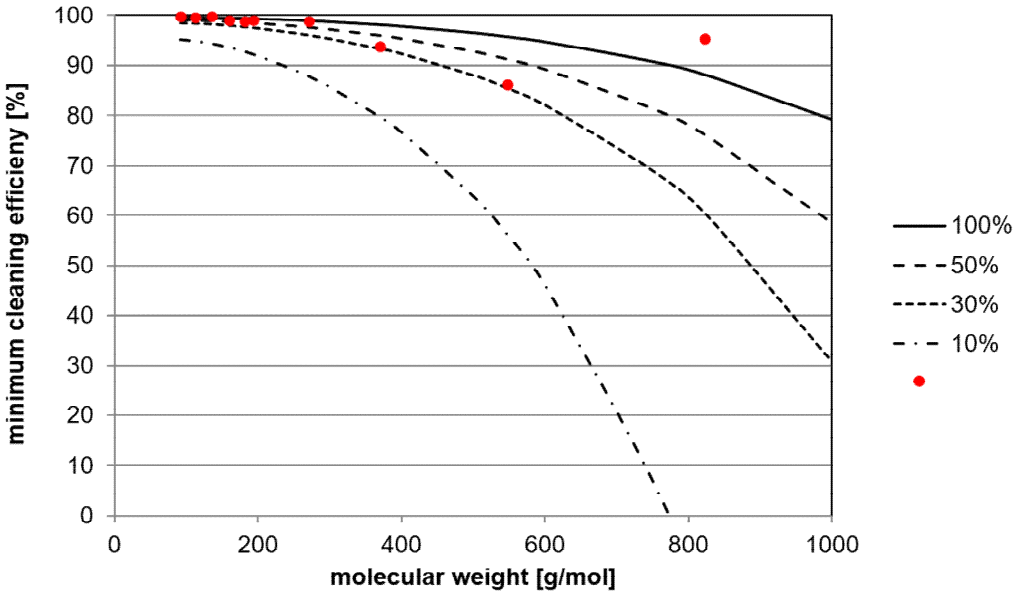


Figure 27: Cleaning efficiencies of surrogates in the challenge test (sample output 14), packaging for solid and liquid food, 40 days at 6 °C, with 250 ml food consumption, initial contamination level **3 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

7.7 Packaging for solid and liquid food, 10 days at 20 °C (960 ml)

Evaluation criteria for packaging for solid and liquid food with post-consumer recyclates are not published till now. However, two EFSA publications on the

evaluation criteria for PET mineral water bottles and HDPE milk bottles can be applied in order to evaluate the HDPE mineral water closures. It should be noted here that EFSA might evaluate the recyclate containing mineral water closures in a different way.

According to the EFSA Scientific opinion on HDPE milk bottles[4] and the (new) EFSA criteria published for PET mineral water bottles[5], the maximum migration of compounds from the post-consumer materials should be below of 0.0626 µg/kg (960 ml consumption of food for a toddler with 12 kg bw). Using migration models, the maximum concentratin of substances of different molecular weights can be calculated using $A_P' = 14.5$ and $\tau = 1577$ K. The maximum concentrations C_{mod} of the applied surrogates were calculated for a food package with 1 l volume package and with an inner surface area of 6 dm^2. The thickness of the packaging was assumed to 300 µm. This maximum concentration corresponds to the assumed migration limit of 0.0626 µg/kg in food. The calculation was done for a food with high solubility for the surrogates (partition coefficient $K_{Polymer/Food} = 1$) at conditions of 10 days at 20 °C with initial contamination levels of 3 mg/kg (similar for PET), 1 mg/kg and 0.5 mg/kg[6]. The results are given in Figure 28 to Figure 30.

Based on the challenge test results a recyclate content of 35.2% (initial contamination level 0.5 mg/kg), 17.6% (initial contamination level 1.0 mg/kg) and 5.9% (initial contamination level 3.0 mg/kg) is possible.

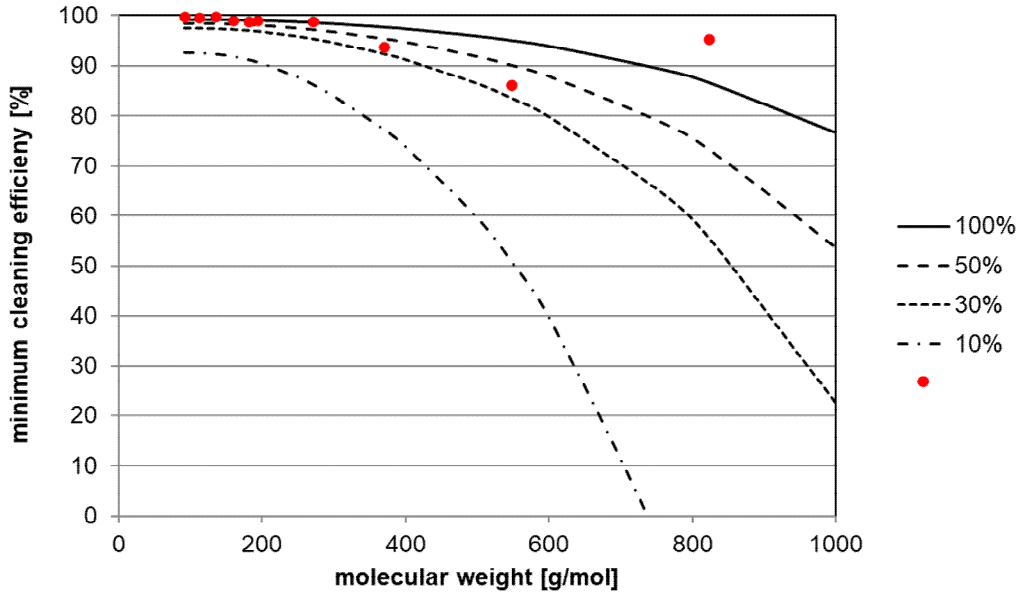


Figure 28: Cleaning efficiencies of surrogates in the challenge test (sample output 14), packaging for solid and liquid food, 10 days at 20 °C, with 960 ml food consumption, initial contamination level **0.5 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

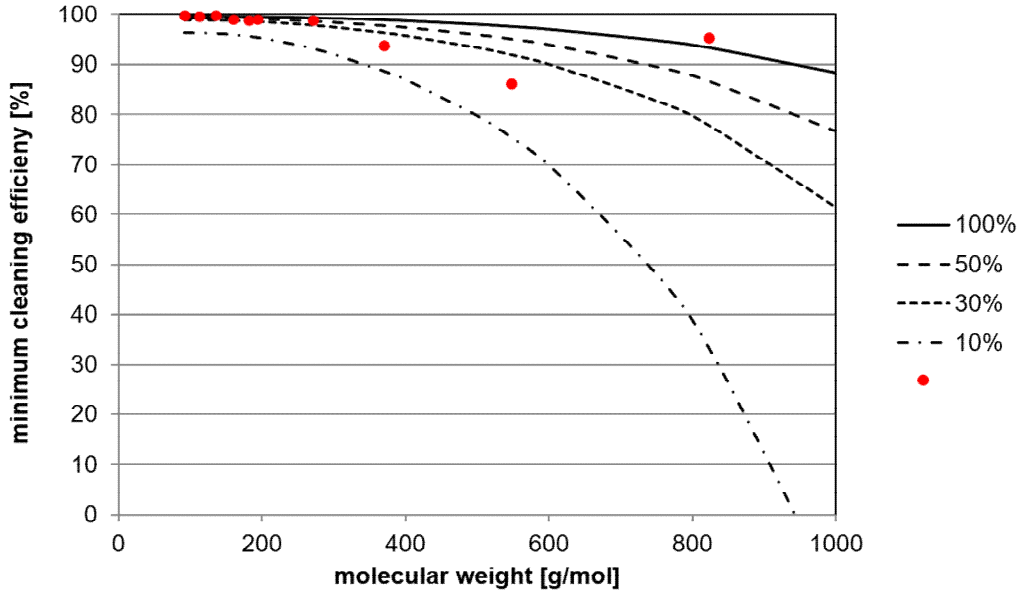


Figure 29: Cleaning efficiencies of surrogates in the challenge test (sample output 14), packaging for solid and liquid food, 10 days at 20 °C, with 960 ml food consumption, initial contamination level **1 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

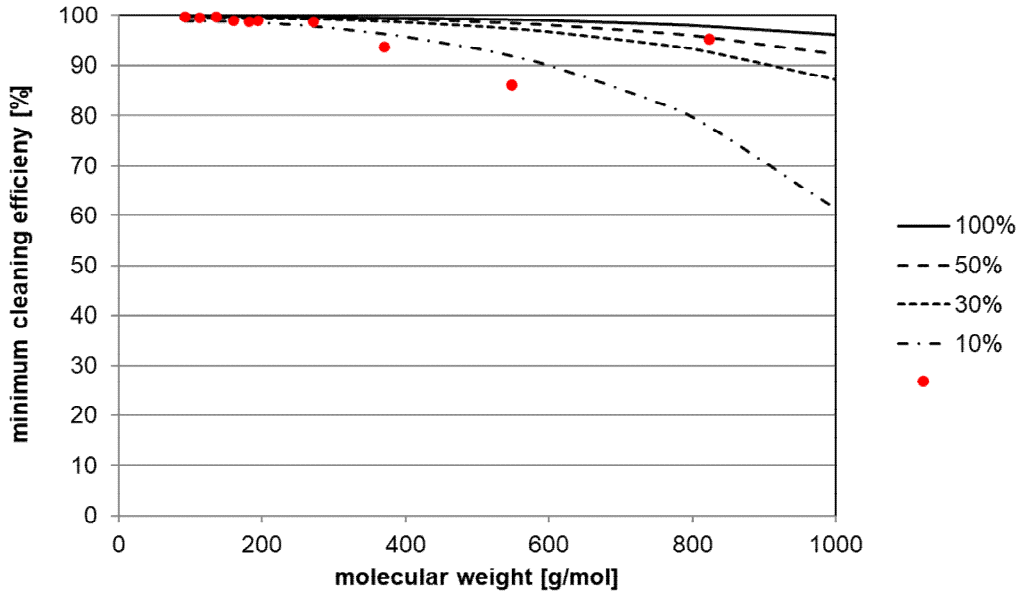


Figure 30: Cleaning efficiencies of surrogates in the challenge test (sample output 14), packaging for solid and liquid food, 10 days at 20 °C, with 960 ml food consumption, initial contamination level **3 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

7.8 Packaging for solid and liquid food, 10 days at 20 °C (350 ml)

The EFSA's food consumption is very high, which consequently limits the potential use of recycled materials in direct contact with food. At the client's

request, lower food consumption figures were therefore also calculated. When using 350 ml food consumption instead of 960 ml, the maximum migration of compounds from the post-consumer materials should be below of 0.171 µg/kg. Using migration models, the maximum concentration of substances of different molecular weights can be calculated using $A_P' = 14.5$ and $\tau = 1577$ K. The maximum concentrations C_{mod} of the applied surrogates were calculated for a food package with 1 l volume package and with an inner surface area of 6 dm^2. The thickness of the packaging was assumed to 300 µm. This maximum concentration corresponds to the assumed migration limit of 0.171 µg/kg in food. The calculation was done for a food with high solubility for the surrogates (partition coefficient $K_{Polymer/Food} = 1$) at conditions of 10 days at 20 °C with initial contamination levels of 3 mg/kg (similar for PET), 1 mg/kg and 0.5 mg/kg[6]. The results are given in Figure 31 to Figure 33.

Based on the challenge test results a recyclate content of 96.2% (initial contamination level 0.5 mg/kg), 48.1% (initial contamination level 1 mg/kg) and 16.0% (initial contamination level 3.0 mg/kg) is possible.

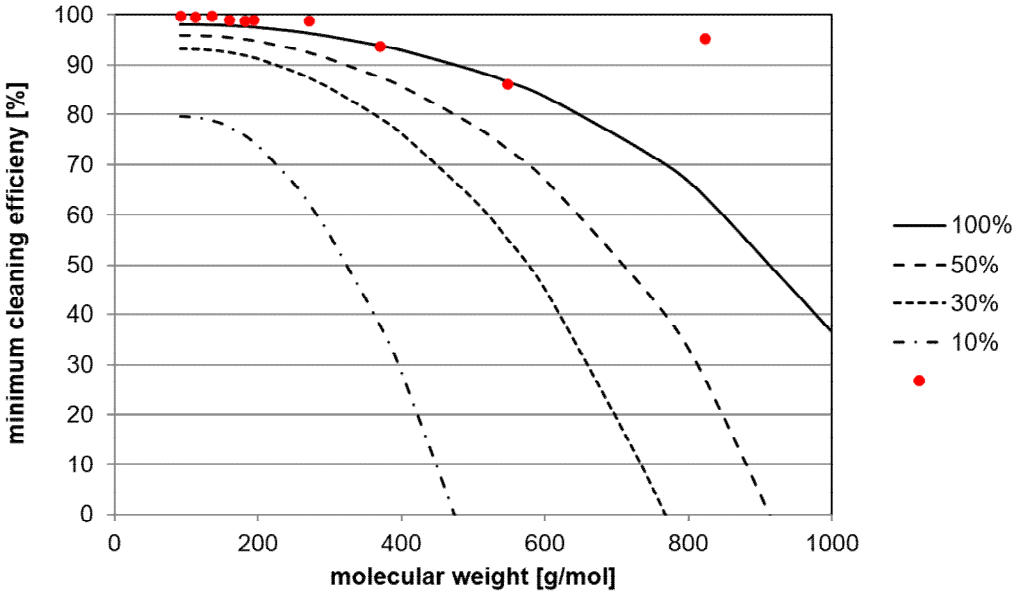


Figure 31: Cleaning efficiencies of surrogates in the challenge test (sample output 14), packaging for solid and liquid food, 10 days at 20 °C with 350 ml food consumption, initial contamination level **0.5 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

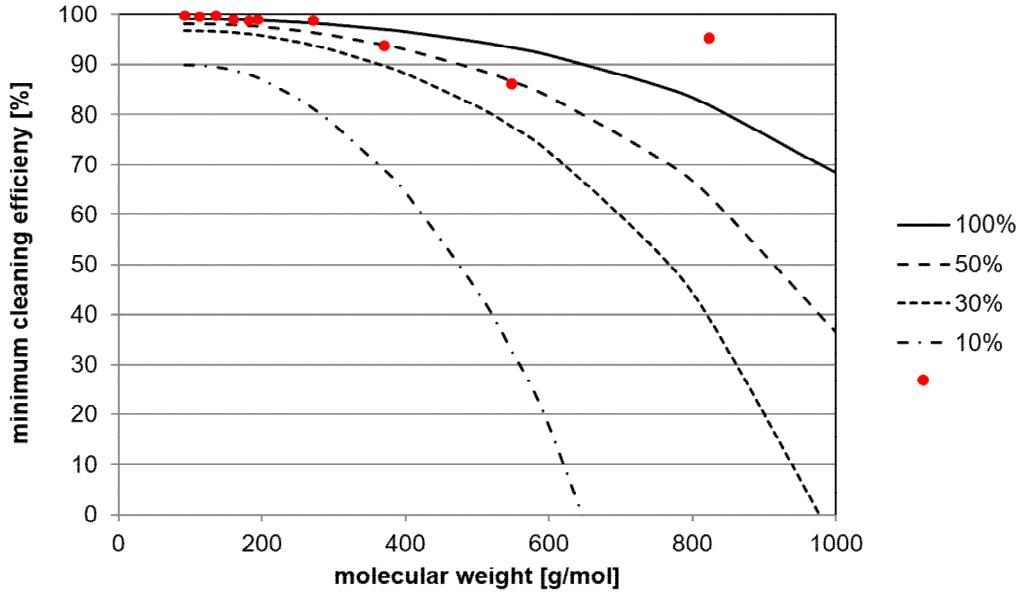


Figure 32: Cleaning efficiencies of surrogates in the challenge test (sample output 14), packaging for solid and liquid food, 10 days at 20 °C, with 350 ml food consumption, initial contamination level **1 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

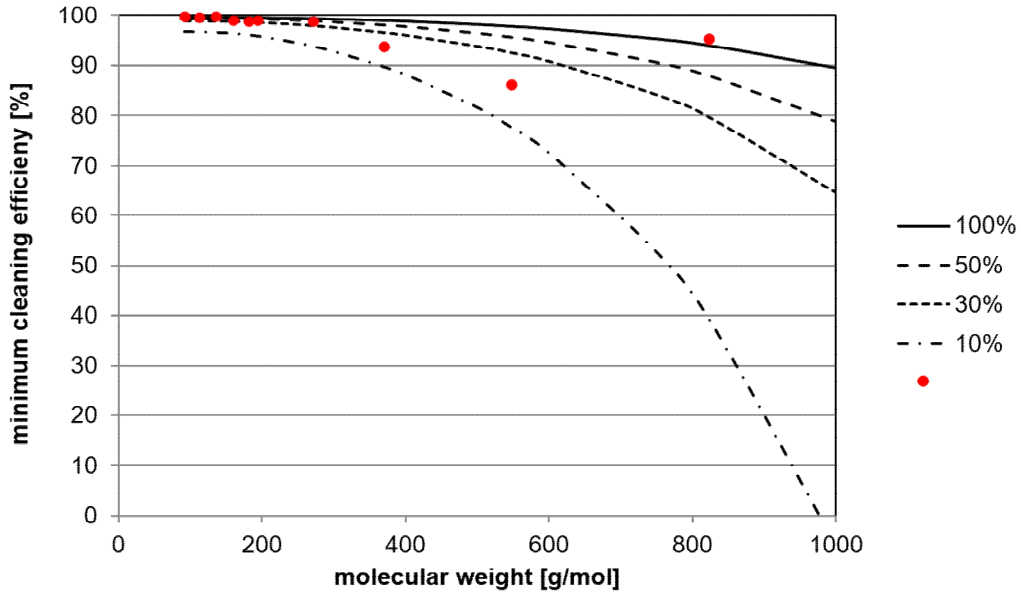


Figure 33: Cleaning efficiencies of surrogates in the challenge test (sample output 14), packaging for solid and liquid food, 10 days at 20 °C, with 350 ml food consumption, initial contamination level **3 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

7.9 Packaging for solid and liquid food, 10 days at 20 °C 250 ml)

The EFSA's food consumption is very high, which consequently limits the potential use of recycled materials in direct contact with food. At the client's

request, lower food consumption figures were therefore also calculated. When using 250 ml food consumption instead of 960 ml, the maximum migration of compounds from the post-consumer materials should be below of 0.240 µg/kg. Using migration models, the maximum concentration of substances of different molecular weights can be calculated using $A_P' = 14.5$ and $\tau = 1577$ K. The maximum concentrations C_{mod} of the applied surrogates were calculated for a food package with 1 l volume package and with an inner surface area of 6 dm^2. The thickness of the packaging was assumed to 300 µm. This maximum concentration corresponds to the assumed migration limit of 0.240 µg/kg in food. The calculation was done for a food with high solubility for the surrogates (partition coefficient $K_{Polymer/Food} = 1$) at conditions of 10 days at 20 °C with initial contamination levels of 3 mg/kg (similar for PET), 1 mg/kg and 0.5 mg/kg[6]. The results are given in Figure 31 to Figure 33.

Based on the challenge test results a recyclate content of 100% (initial contamination level 0.5 mg/kg), 67.5% (initial contamination level 1 mg/kg) and 22.5% (initial contamination level 3.0 mg/kg) is possible.

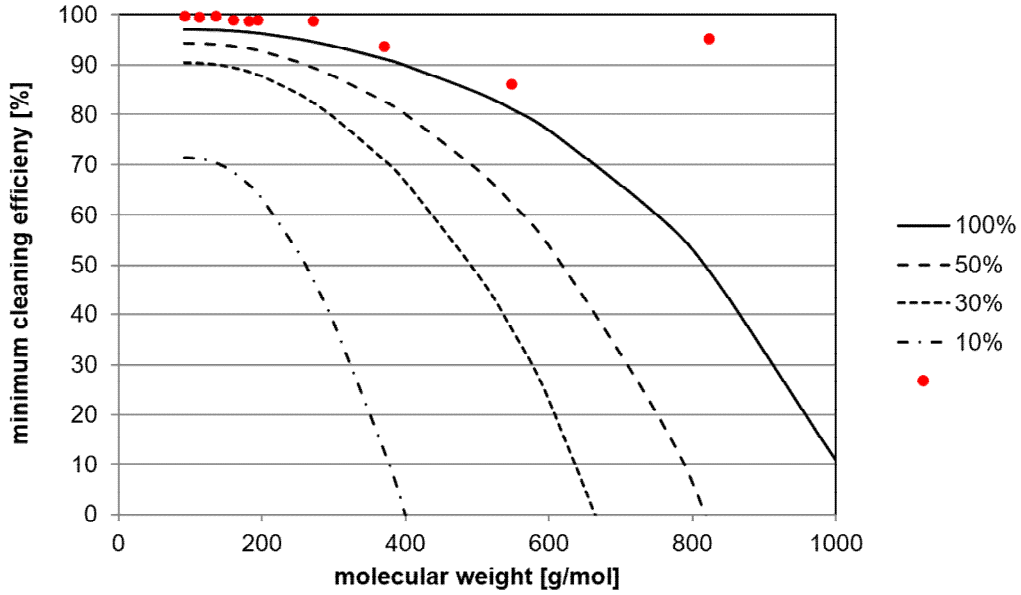


Figure 34: Cleaning efficiencies of surrogates in the challenge test (sample output 14), packaging for solid and liquid food, 10 days at 20 °C with 250 ml food consumption, initial contamination level **0.5 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

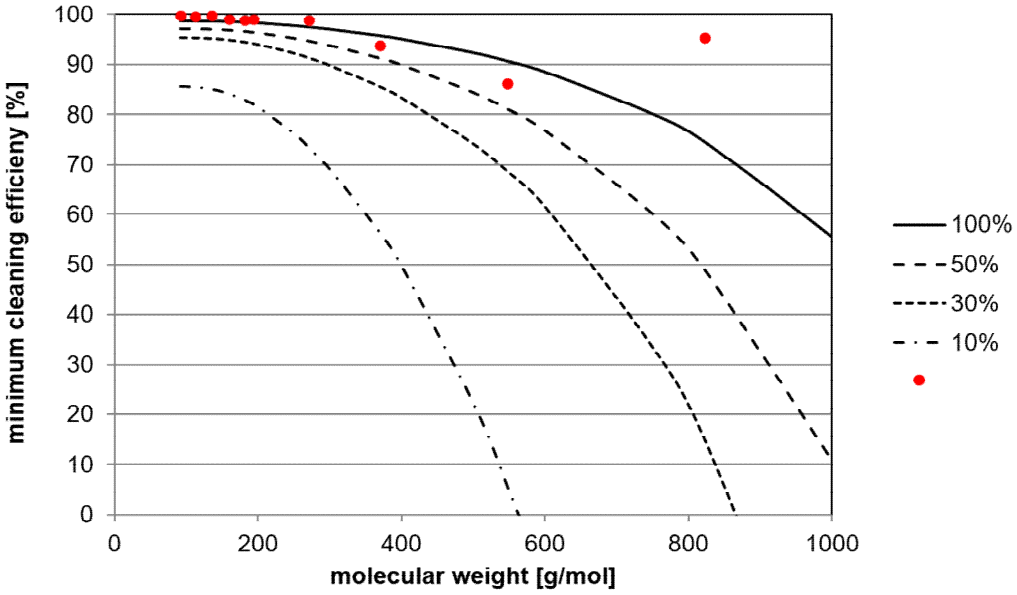


Figure 35: Cleaning efficiencies of surrogates in the challenge test (sample output 14), packaging for solid and liquid food, 10 days at 20 °C, with 250 ml food consumption, initial contamination level **1 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

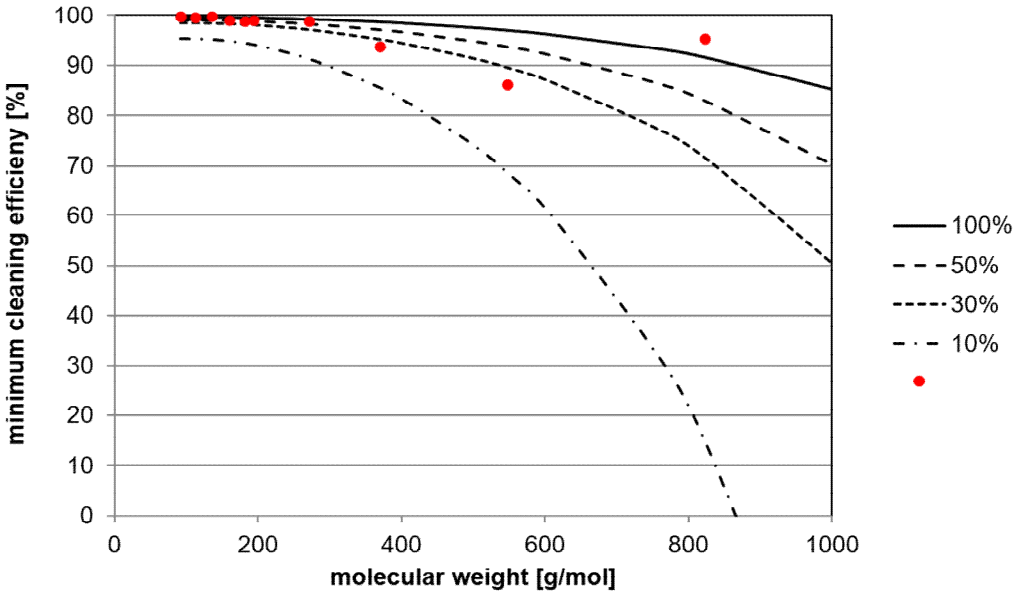


Figure 36: Cleaning efficiencies of surrogates in the challenge test (sample output 14), packaging for solid and liquid food, 10 days at 20 °C, with 250 ml food consumption, initial contamination level **3 mg/kg**). Lines: Minimum cleaning efficiency, red dots: experimental data

8 Conclusions

Within the study, a challenge test with artificially contaminated HDPE material was performed in order to determine the cleaning efficiency of the investigated HDPE super-clean recycling process.

The challenge test data were evaluated according to the published EFSA opinion on HDPE milk bottles. In addition, further applications e.g. closures for mineral water and softdrink bottles as well as packaging for solid and liquid food were evaluated. For these applications, however, evaluation criteria are not published by EFSA till now. The evaluation criteria applied in this study, were therefore derived from two EFSA opinions on PET mineral water bottles as well as on HDPE milk bottles. This is under the assumption that EFSA will evaluate post-consumer HDPE recyclates in a similar way. In addition, the calculations are based on an input contamination level of 0.5 mg/kg, 1 mg/kg and 3 mg/kg (similar to PET) in post-consumer HDPE published by EFSA for HDPE milk bottles.

As expected, the high molecular weight substances are the most-challenging substances for the investigated super-clean recycling process. Sample 14 was used for the evaluation regarding the EFSA requirements for milk bottles and the assumed EFSA criteria for closures and packaging for packaging for solid and liquid food.

The percentages of HDPE recyclates, which can be applied under the investigated storage conditions are given in Table 5.

Table 5: Percentages of HDPE recyclates in the investigated applications

application	storage conditions	Food consump-tion [g/kg bw day]	initial contamination level		
			0.5 mg/kg	1 mg/kg	3 mg/kg
milk bottles	15 days at 5 °C	90	83.2%	/	/
closures for mineral water	365 days at 25 °C	260	100%	100%	39.0%
closures for softdrinks	365 days at 25 °C	80	100%	100%	100%
packaging for solid and liquid food	40 days at 6 °C	80	49.2%	24.6%	8.2%
		29.2	100%	67.3%	22.4%
		20.8	100%	94.4%	31.5%
packaging for solid and liquid food	10 days at 20 °C	80	35.2%	17.6%	5.9%
		29.2	96.2%	48.1%	16.0%
		20.8	100%	67.5%	22.5%

The most challenging substances are the high molecular weight substances DEHA and TEHTM. I should be noted that the calculations were done with a partition coefficient of K = 1 which represents good solubility of the substances in the contact media. This approach was used by EFSA for all calculations on PET and HDPE. However, for high molecular weight substances good solubility in the contact media is most unlikely. Lower solubility will result in higher partitioning coefficients, which will increase the maximum recyclate amounts in the milk bottles, closures and other packaging applications. On the other hand, realistic data on solubility of the applied surrogates in milk, water, softdrinks and food as well as realistic partitioning coefficients are rare in the scientific literature. Therefore, the worst-case approach with K = 1 was applied in this study.

Fraunhofer Institute
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Freising, October 9, 2026

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Annotation: This report replaces the Fraunhofer Test report PA-1288b-24 of 07.08.2026. Samples contamination treatment was corrected.