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Influence of Natural Waters on the Leaching of Sewer Rehabilitation Resins

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Abstract

The leaching behavior of bisphenol A (BPA) remains a significant environmental concern. Despite EU regulatory restrictions and the World Health Organization (WHO) establishing precautionary values for human exposure to this monomer, BPA is still widely used in polymer-based products, including materials for sewer rehabilitation. Standard leaching assessments typically employ deionized water, although natural waters represent actual field conditions. This study investigates the release of BPA and its substitute, bisphenol F (BPF), from an epoxy resin system and a vinyl ester resin system. Sample discs (0.5 cm in height and 11 cm in diameter) were subjected to dynamic surface leaching tests using groundwater and tap water as leaching media. Eluate replacement intervals followed the standardized Dynamic Surface Leaching Test (DSLT; EN 16637-2), marking the first application of natural waters within this standardized test procedure. The detection limit for the gas chromatography analyses was 0.001 µg/L. Compared with the deionized water prescribed by the standard, natural waters resulted in significantly higher cumulative releases of BPA and BPF, with cumulative BPA release increasing by factors of 5.2–9.2 to a maximum of 0.412 mg/m^2. These findings indicate that the standardized 64-day DSLT may underestimate environmentally relevant emissions and that permissible cumulative release values, derived from modeling and regulatory thresholds, may not be maintained under environmentally relevant conditions. GC–MS screening and the Umu test showed no evidence of genotoxic effects in the leachates. Exploratory analysis suggested a positive relationship between BPA release and pH (R^2 = 0.79). Overall, the results demonstrate that the choice of leaching medium strongly influences measured emissions and should therefore be reconsidered in assessment frameworks for polymer-based construction materials to better reflect environmentally relevant conditions.

Keywords: bisphenol A; bisphenol F; dynamic surface leaching test; sewer rehabilitation; groundwater; environmental risk assessment

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1. Introduction

In this study, the leaching behavior of an epoxy resin system and a vinyl ester resin system, both intended for use in sewer rehabilitation products, was investigated using various natural waters. The influence of natural waters on the leaching behavior of bisphenol A (BPA) and bisphenol F (BPF) from sewer rehabilitation resins has not previously been investigated using the standardized Dynamic Surface Leaching Test (DSLT), despite the fact that

groundwater and seepage water represent the environmentally relevant exposure media under field conditions. The need to renew aging sewer infrastructure is well documented worldwide [1–5]. Consequently, the demand for resin systems that have proven effective in trenchless pipe rehabilitation, whether for small-diameter residential pipes or large sewer systems, continues to increase [6,7]. Bisphenol A (BPA; 4,4′-isopropylidenediphenol; Figure 1), with a molecular length of approximately 10 Å (1 nm), is one of the most widely produced industrial chemicals worldwide, with an annual production exceeding three million tonnes [8].

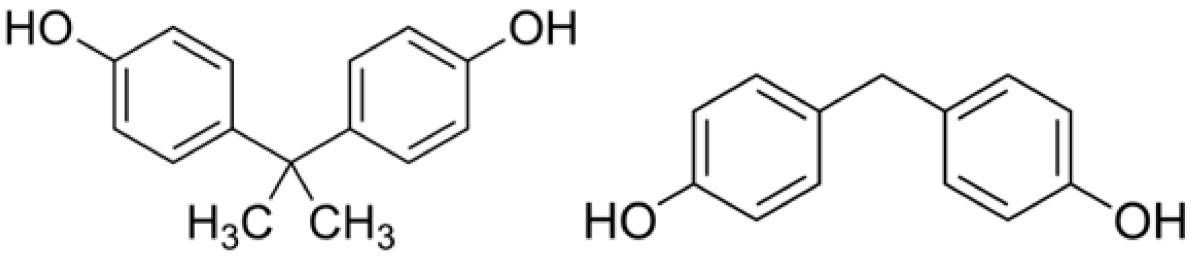


Figure 1. Chemical structural formulas of BPA (**left**) and BPF (**right**).

Since BPA (CAS No. 80-05-7) is an endocrine disruptor, it was added to the REACH Candidate List in January 2018 and classified as a substance of very high concern (SVHC) for human health and the environment [9]. Concerns have arisen regarding the release of BPA and its substitute bisphenols from resin systems used in sewer rehabilitation [6–8]. BPF has not yet been classified as an endocrine disruptor under the REACH Regulation. In 2015, the Swedish government submitted a proposal to the European Chemicals Agency (ECHA) to ban the use of BPA-containing resin systems for relining drinking water pipes; however, the proposal was withdrawn in the same year [10]. According to ECHA's legislation profile for the EU Drinking Water Directive, BPA is included on the European positive lists only for specific technical functions, such as an additive in plastics and as an organic constituent of cementitious materials. The maximum allowable migration into drinking water is 2.5 µg/L [11]. The adverse effects of BPA (Figure 1) and its substitute bisphenols on the environment and living organisms remain the subject of ongoing debate [12–16]. In addition, resin systems used in sewer rehabilitation products may leach other potentially harmful organic substances into the environment [17–19]. This issue was investigated in [20] and warrants further investigation using natural leaching media. As an endocrine disruptor, BPA exhibits a substantially higher susceptibility to oxidative degradation than, for example, its substitute bisphenol S (BPS) [21].

In a previous study [20], deionized water was used as the leaching medium. An epoxy resin system (R1) exhibited a cumulative BPA release of 0.061 mg/m^2 in the Dynamic Surface Leaching Test (DSLT), performed according to EN 16637-2:2023 [22] over a period of 64 days. This test method was selected because it most accurately reflects the release of organic and inorganic substances from resin systems used in sewer rehabilitation products [20]. A vinyl ester resin system (R3) exhibited a cumulative BPA release of 0.086 mg/m^2 over the same test period. The evaluation concept described in [23] was applied to establish an upper release limit for groundwater protection, assuming a worst-case scenario in which the rehabilitated pipe is located below the groundwater table. As the groundwater concentration limit, the insignificance threshold of the Environmental Quality Standard (EQS) [24] of 1.7×10^{-4} µg/L was applied. Based on the model scenario and boundary conditions described in [23], a cumulative release of 0.085 mg/m^2 in the DSLT corresponds to this concentration at the point of compliance. The resin systems investigated in [20] generally complied with this upper limit. However, natural waters contain dissolved ions, including calcium, potassium, sodium, chloride, and sulfate [24],

and typically exhibit higher pH values and electrical conductivities than the deionized water prescribed as the leaching medium in the standardized DSLT. In the present study, various analytical methods were applied to investigate the influence of naturally occurring water constituents on the leaching behavior of BPA and BPF. Chemical transformations and degradation pathways of BPA have been reported in numerous studies [25–34]. Based on theoretical considerations and previous findings, higher BPA concentrations are expected in eluates obtained using natural leaching media because of their higher pH values and ionic strengths [35].

2. Materials and Methods

2.1. Materials

2.1.1. Resins

Two commercial resin formulations previously investigated by Ahrens et al. [20] were selected: R1, an epoxy resin system containing an active monomer, and R4, a vinyl ester resin system. Resin system R4 was selected because it exhibited the highest estrogenic activity among the sewer rehabilitation products investigated in the previous study.

2.1.2. Leaching Media

In addition to deionized water (DW), three natural waters were investigated: groundwater from Schenkenhorst, Brandenburg (GW1), groundwater from Reichswald (GW2), and tap water from Aachen (TW). A second batch of GW2 (GW2*) was used for the experiments with resin system R4. The leaching media were characterized in terms of pH [36], electrical conductivity [37], water hardness [38], dissolved organic carbon (DOC), and elemental composition determined by inductively coupled plasma optical emission spectrometry (ICP-OES) [39] and, for GW2*, by inductively coupled plasma mass spectrometry (ICP-MS) [40]. Chloride and sulfate concentrations were determined by ion chromatography. ICP-OES and ICP-MS were calibrated using a multi-element standard (Roth; Art. No. 2650.1). The calculated German hardness values, based on the calcium and magnesium concentrations determined by elemental analysis, were in good agreement with the results obtained by complexometric titration. According to the German hardness classification, both groundwater samples were classified as hard (14–21.3 °dH), whereas the Aachen tap water was classified as soft (<7.3 °dH). The concentrations of fluoride (F^-), nitrate (NO_3^-), and nitrite (NO_2^-) were below the limit of quantification (LOQ; 0.1 mg/L). The BPA and BPF concentrations in the blank water samples were determined by GC–MS according to [41]. The total chlorine concentration (Cl_2) was determined using a photometric cuvette test [42]; however, chlorine was not detected in any of the water samples (<LOQ = 0.05 mg/L). The resulting water chemistry data are summarized in Table 1. Prior to use, the natural water samples were stored frozen, thawed, and filtered using Whatman Grade 595 ½ filter paper (4–7 µm; Cytiva, Maidstone, UK). The precipitates formed during storage were identified as calcite by X-ray diffraction (XRD) [43].

2.2. Sample Preparation

Resin discs were prepared as described previously [20], with a diameter of 11 cm and a thickness of 5 mm. The specimens were tested after seven days of curing to represent the minimum realistic age that may occur between installation and environmental exposure under field conditions. Representative specimens of resin systems R1 and R4 are shown in Figure 2.

Table 1. Characterization of the leaching media (blank samples).

Parameter of the Blank Sample		Unit	Deionized Water	Groundwater 1	Groundwater 2 [1]		Tap Water
					Batch 1	Batch 2	
pH		-	5.88	7.88	8.04	7.61	8.12
electrical conductivity		µS/cm	1.89	819	520	572	212
Calcium		mg/L	<0.01	115	100	72.4	20.5
Magnesium			<0.01	16.6	11.4	10.5	6.91
Sodium			<0.01	42.6	13.4	12.9	11.9
Potassium			<0.01	3.69	1.25	1.35	1.35
Sulfur	elementary		<0.2	76.5	40.5	33.5	11.0
	Converted to SO_4^{2-}		<0.6	229	121	100	32.9
Silicon			<0.01	3.14	4.36	5.41	1.41
Dissolved Organic Carbon			<1	3.6	2.6	2.7	2.4
Barium		µg/L	<1	17.1	41.1	32.9	6.57
Boron			<1	49.1	10.6	11.5	3.73
Copper			<1	<1	<1	1.09	3.30
Strontium			<1	181	194	176	26
Zinc			<1	15.0	<1	<1	48.3
Bisphenol A			0.110	0.001	0.034	0.087	0.010
Bisphenol F			0.003	0.002	0.001	0.002	0.002
Water hardness	According to DIN 38406-3 [38]	°dH	0.0	16.0	12.7	11.3	3.2
	Calculated via ICP (Ca^{2+}, Mg^{2+})		0.0	19.9	16.6	12.6	4.5
Ion chromatography	SO_4^{2-}	mg/L	0.0	208.0	85.1	84.2	20.4
	Cl^-		0.0	80.9	37.3	39.2	10.7

Note: [1]: A second batch of groundwater 2 (GW2*) was provided for leaching tests with resin R4.

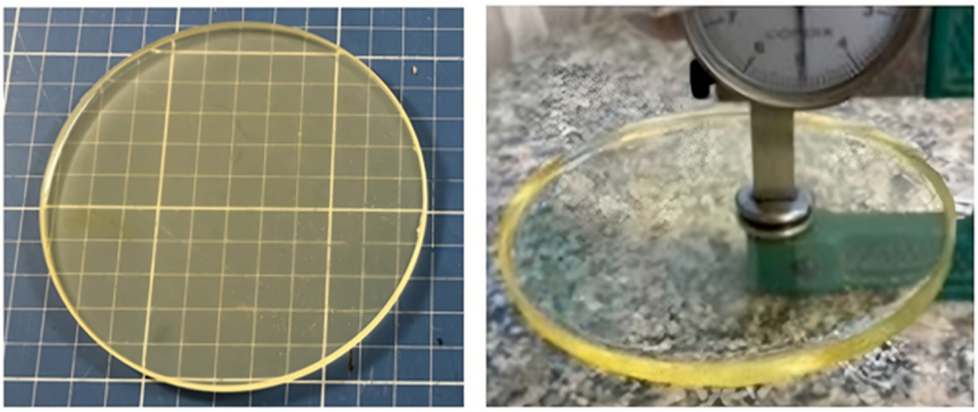


Figure 2. Samples of the epoxy resin system R1 (**left**) and vinyl ester resin system R4 (**right**).

2.3. Dynamic Surface Leaching Test (DSLT)

Leaching experiments in this study were performed according to [22]; the justification for the applied experimental setup has been provided in [20]. Three resin discs were placed on a stainless-steel sample holder inside a glass cylinder (Figure 3), resulting in a total exposed surface area of 621 cm^2.

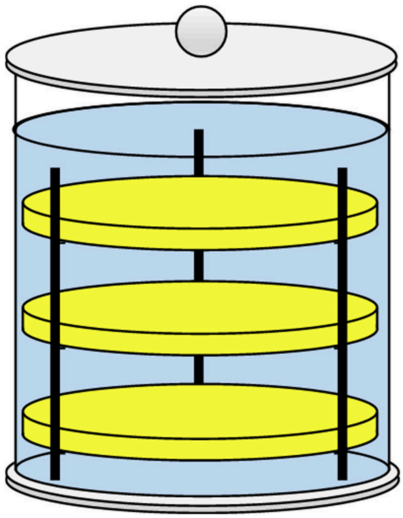


Figure 3. Schematic of the DSLT experimental setup, as used in [20].

The eluate volume was adjusted to maintain the prescribed liquid-to-surface-area ratio of 20 L/m^2 [44]. The tests were conducted at 20 °C using either deionized water, as prescribed by the standard, or natural waters as the leaching media. Eluates were collected after 0.25, 1, 2.25, 4, 9, 16, 36, and 64 days. Between sampling events, the specimens were protected from light exposure to minimize photodegradation [45]. For each eluate, pH, electrical conductivity, dissolved organic carbon (DOC), BPA, and BPF were determined. In selected experiments, additional analyses included ion chromatography (Cl^- and SO_4^{2-}), flame photometry (Ca^{2+}, Na^+, and K^+), semi-quantitative GC–MS screening [46], and the Umu test for genotoxicity [47]. The cumulative release (R_n; mg/m^2) was calculated according to EN 16637-2:2023 using Equation (1):

$$R_n = \sum_{i=1}^{n} R_i = \sum_{i=1}^{n} c_i \cdot \frac{L}{A} \quad (1)$$

where c_i is the concentration in eluate i (mg/L) and L/A is the liquid-to-surface-area ratio (20 L/m^2).

2.4. Analytical Methods

BPA and BPF were quantified by GC–MS according to [41]. Prior to analysis, the samples were enriched by solid-phase extraction and subsequently derivatized. Genotoxicity was evaluated using the Umu test according to DIN 38415-T3:1996-12 [48]. Eluates from the first and seventh sampling intervals of resin system R4 were selected for analysis to represent early-stage and long-term release conditions [22,44].

2.5. Experimental Design

Table 2 summarizes the test matrix. Most leaching experiments were performed in triplicate, whereas two experimental variants were conducted in duplicate. Based on the low variability observed in the previous study [20], pooled eluates were considered sufficient for several analyses.

Microsoft Excel (Microsoft Corporation, Redmond, WA, USA) was used for the graphical presentation of the results.

Table 2. Test Matrix for epoxy resin R1 and vinyl ester resin R4 (7-day-old samples).

Leaching Medium	R1 (Epoxy Resin with Active Monomer Addition)	R4 (Vinyl Ester Resin; Highest ERα-CALUX Value in [20])
Deionized water	, [20]	batch 1 , [20]
		batch 2
Leaching Medium	batch 2	batch 2
Groundwater GW1		-
Groundwater GW2		
Tap water (Aachen)		-

Notes: : Analysis of bisphenols in the mixed eluate of three replicate test set-ups; : Analysis of the bisphenols in the individual eluates; : Analysis of bisphenols in the mixed eluate of two replicate test set-ups.

3. Results

3.1. pH, Electrical Conductivity and Dissolved Organic Carbon from Epoxy Resin R1

The pH values of the DSLT eluates obtained using the different natural waters with resin system R1 showed only minor differences compared with the corresponding blank values. Across all three natural leaching media, the pH ranged from 7.76 to 8.84 (Figure 4). In contrast to the deionized water used in the experiments with batch 1, higher pH values were observed throughout the leaching test.

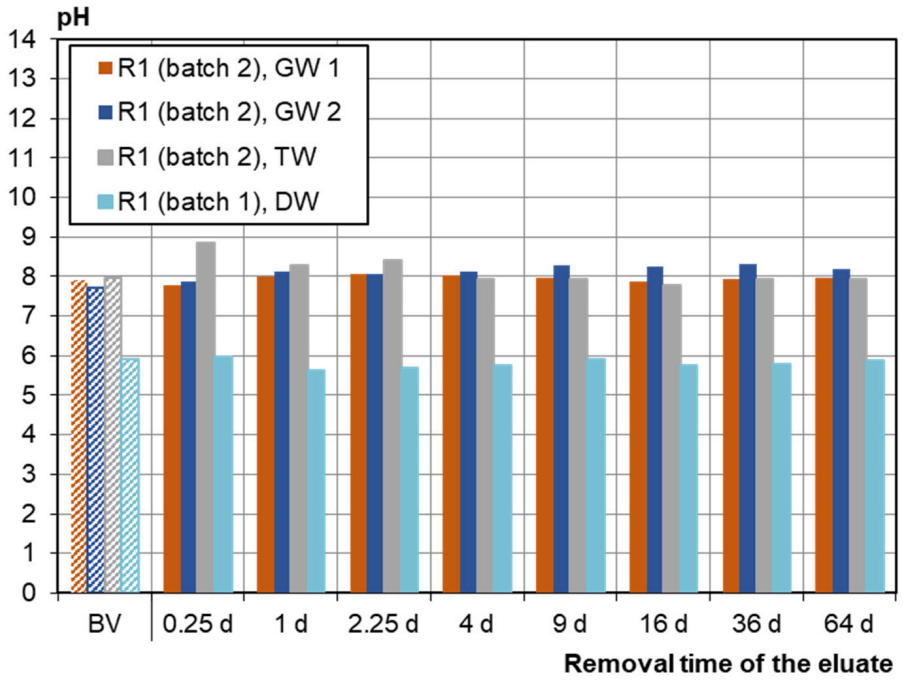


Figure 4. pH values of DSLT eluates after leaching of the sewer renovation product R1 with natural waters, compared with the blank value (BV).

The electrical conductivity of the natural waters was significantly higher than that of deionized water (Figure 5). Measured values ranged from 219 µS/cm for Aachen tap water to 950 µS/cm for Groundwater 1, whereas Groundwater 2 exhibited consistently lower conductivity values of approximately 500 µS/cm. A graphical representation of the dissolved organic carbon (DOC) concentrations measured after each eluate collection is shown in Figure 6.

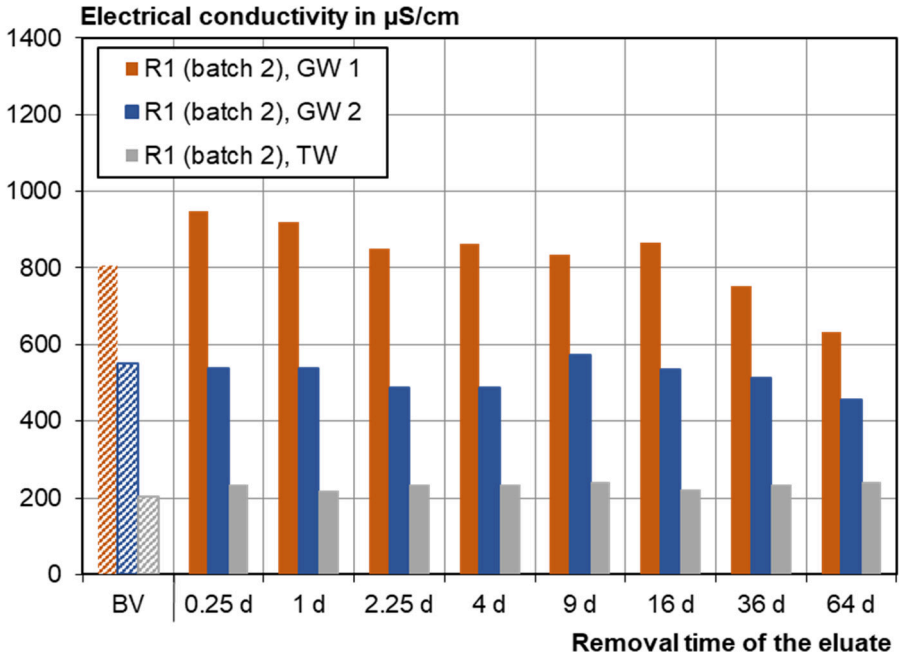


Figure 5. Electrical conductivity values of DSLT eluates after leaching of the sewer renovation product R1 using natural waters, compared with the blank value (BV).

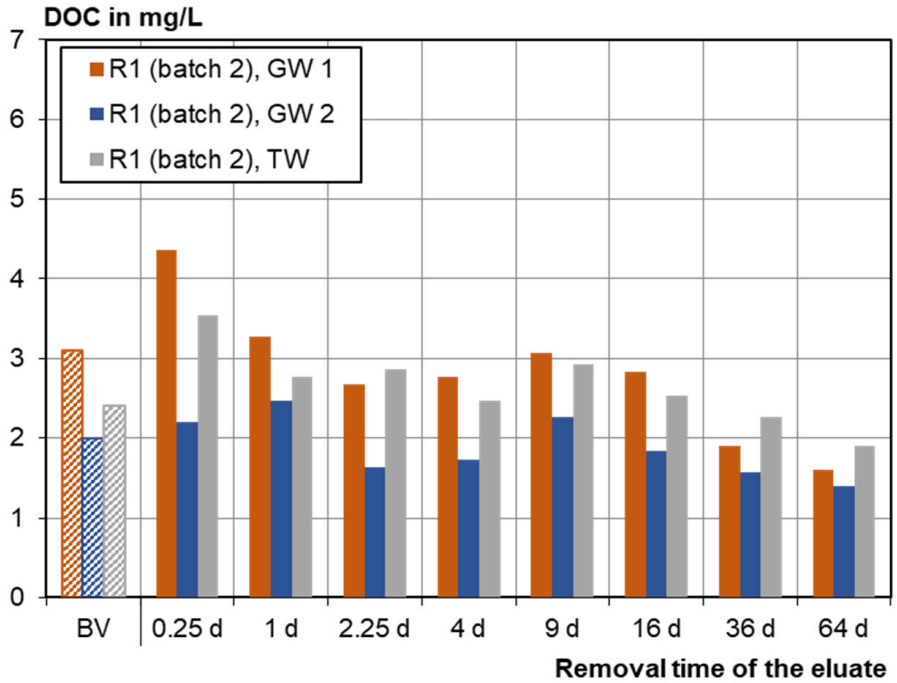


Figure 6. Dissolved organic carbon (DOC) concentrations in DSLT eluates after leaching of the sewer renovation product R1 using natural waters, compared with the blank value (BV).

3.2. Release of BPA and BPF from Epoxy Resin R1

A substantially higher cumulative release (R_{64d}) was observed for resin system R1 when natural leaching media were used. The cumulative releases of bisphenol A (BPA) and bisphenol F (BPF) from the different leaching media are illustrated in Figures 7 and 8, respectively. The highest cumulative BPA release was observed for groundwater GW2. BPA and BPF releases were not corrected for blank values, as minor contamination from other sources cannot be ruled out. In this study, an increased release of BPF during the DSLT was also observed when two natural waters were used as leaching media. Only groundwater GW1 and Aachen tap water are included in the BPF release graph, as BPF concentrations in eluates obtained with deionized water and GW2 were only slightly above the detection limit (0.001 µg/L). Notably, the increased BPA release observed when natural waters were used as leaching media did not necessarily correspond to an increased BPF release.

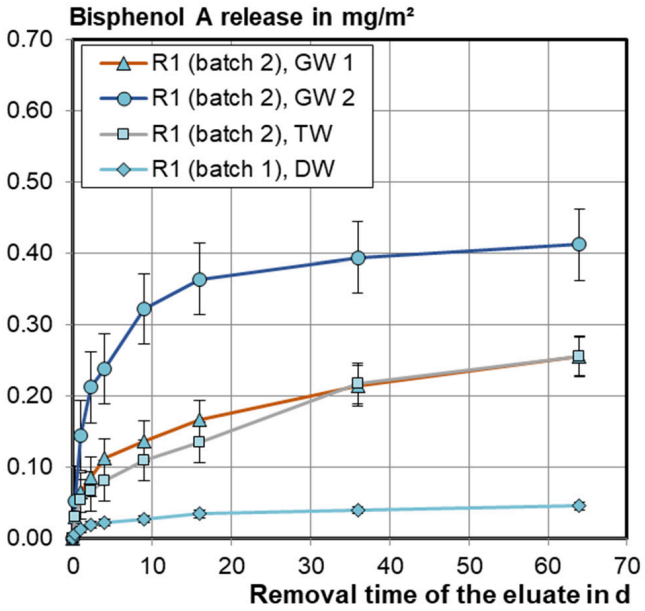


Figure 7. Cumulative releases of BPA from epoxy resin R1, including standard errors.

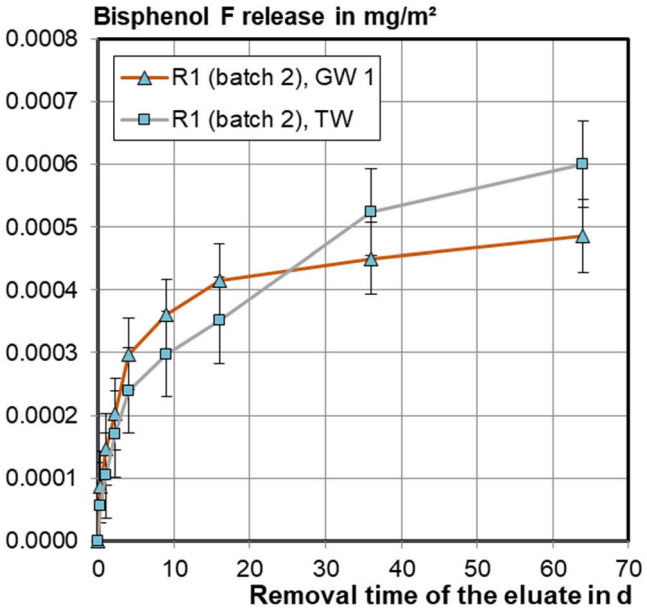


Figure 8. Cumulative releases of BPF from epoxy resin R1, including standard errors.

3.3. pH, Electrical Conductivity and DOC from Vinyl Ester Resin R4

The pH values of the eluates from the second batch of resin system R4 were very similar to those of the first batch, with both batches leached using demineralized water (DW) (Figure 9). Up to the fourth eluate sampling, the pH values were nearly identical. Thereafter, the pH of the first batch increased from 6.1 to 6.7, whereas that of the second batch decreased to below 6. In contrast, when groundwater 2 (GW2*; batch 2) was used as the leaching medium, the pH of the individual eluate samples remained consistently higher, at approximately 8. The progression of the electrical conductivity is shown in Figures 10 and 11.

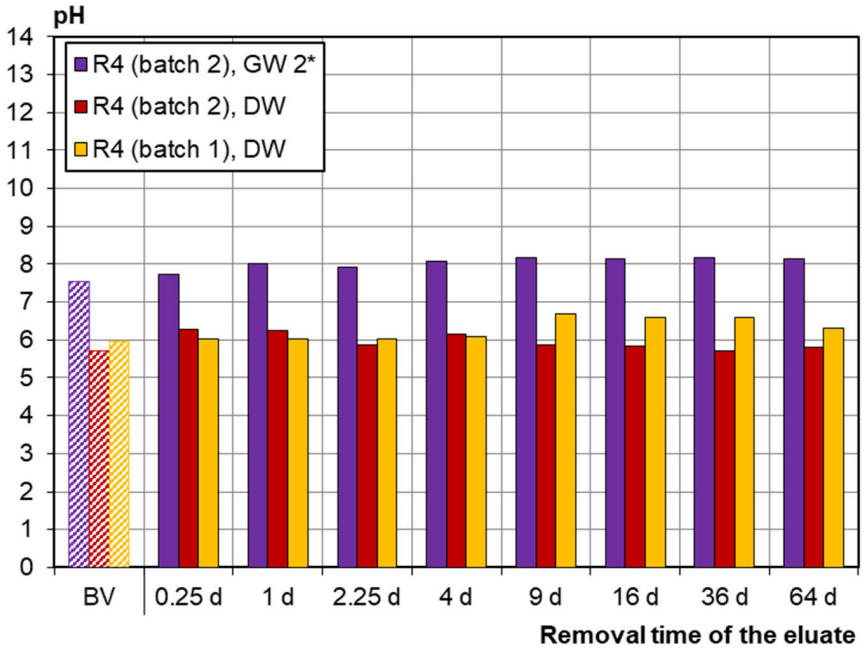


Figure 9. pH values of DSLT eluates after leaching of the sewer renovation product R4 using deionized water (DW) and groundwater GW2*, compared with the blank value (BV).

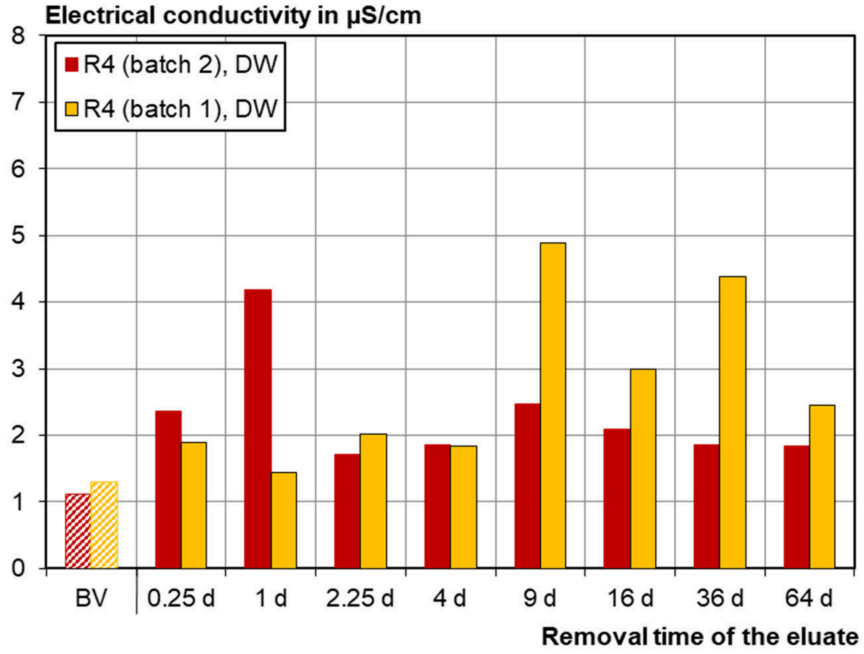


Figure 10. Electrical conductivity of DSLT eluates after leaching of the sewer rehabilitation product R4 using deionized water (DW), compared with the blank value (BV).

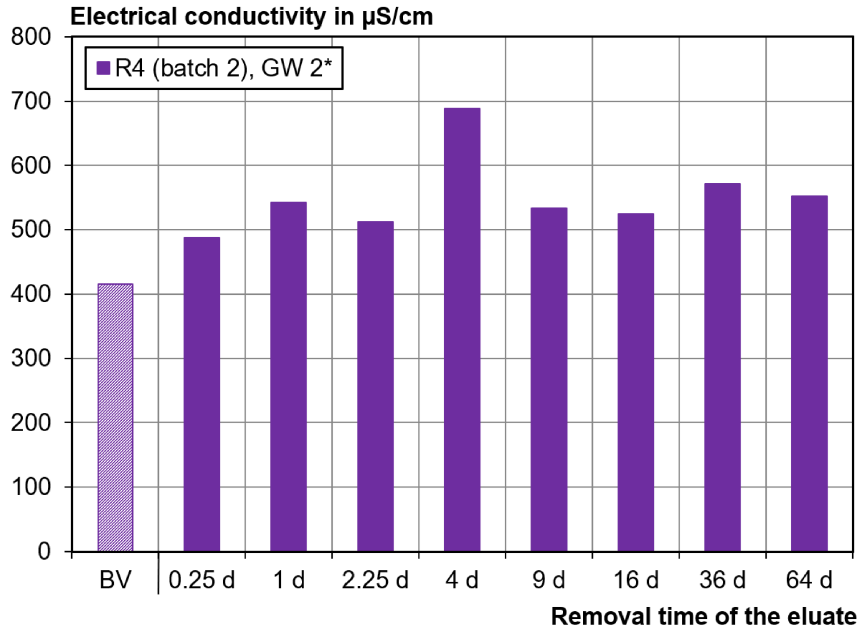


Figure 11. Electrical conductivity of DSLT eluates obtained from leaching the sewer rehabilitation product R4 with groundwater GW2*, compared with the corresponding blank value (BV).

The DOC concentrations in the eluates obtained from both batches using deionized water (Figure 12) were often below the limit of quantification (LOQ; 1 mg/L) and were therefore set equal to the LOQ for graphical representation. In contrast, significantly higher DOC concentrations were measured when groundwater GW2* was used as the leaching medium. The seventh eluate sample, which was also analyzed using the Umu test, exhibited the highest DOC concentration (5.9 mg/L). The concentrations of Ca^{2+}, Na^{+}, K^{+}, Cl^{-}, and SO_4^{2-} measured after each eluate renewal were comparable to those of the corresponding blank samples (Supplementary Materials, Table S1).

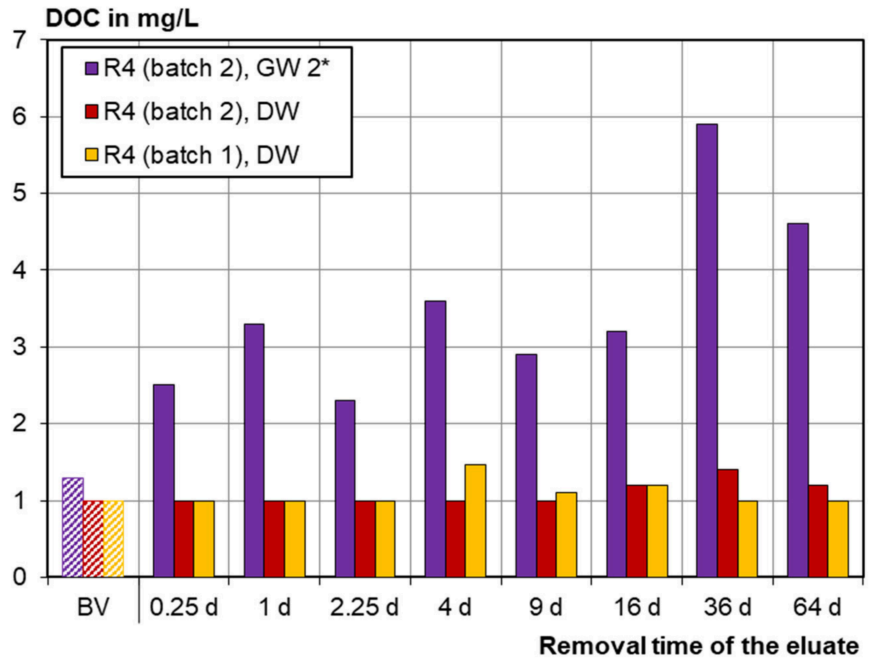


Figure 12. Dissolved organic carbon (DOC) concentrations in DSLT eluates after leaching of the sewer renovation product R4 using deionized water (DW) and groundwater GW2*, compared with the blank value (BV).

3.4. BPA and BPF Release from Vinyl Ester Resin R4

Figures 13 and 14 present the BPA and BPF results for the different batches and leaching media. The cumulative BPA release from the same batch of resin system R4 in the DSLT was 1.8-fold higher when groundwater was used as the leaching medium. The cumulative BPF release increased by more than a factor of two when GW2 or Aachen tap water was used. As in the previous experiments, BPA and BPF releases were not corrected for blank values.

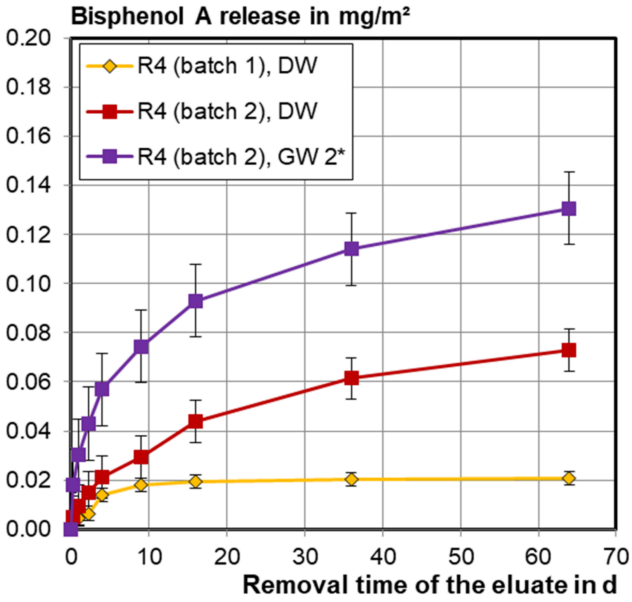


Figure 13. Cumulative releases of BPA from vinyl ester resin R4, including standard errors.

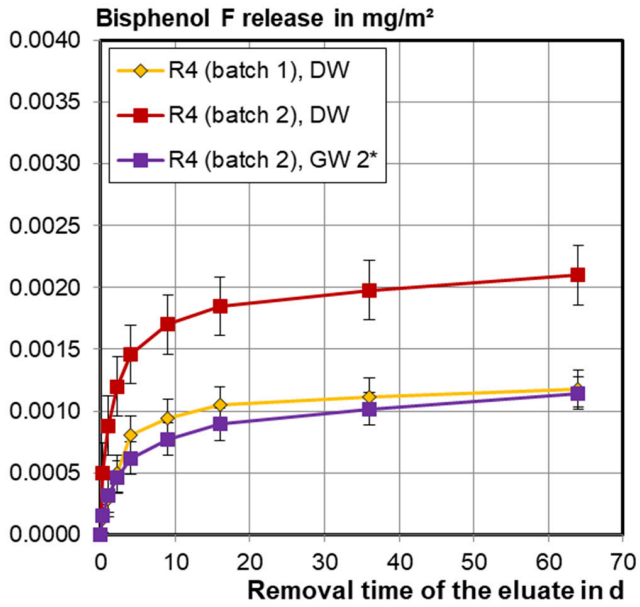


Figure 14. Cumulative releases of BPF from vinyl ester resin R4, including standard errors.

3.5. Summarizing Overview of the BPA/BPF Release

Table 3 summarizes the cumulative release of bisphenol A (BPA) and bisphenol F (BPF) from two batches of the sewer renovation products epoxy resin R1 and vinyl ester resin R4. To evaluate the release mechanisms of BPA and BPF in different leaching media according to [22], the root mean square error (RMSE) of the measured monomer concentrations was calculated (Table 4). An RMSE value of <0.40 indicates diffusion-controlled release.

Additional release mechanisms were evaluated (Table 5). Surface leaching is indicated when the pH difference between the first eluate (pH_1) and the mean pH of the subsequent eluates ($pH_{2–8}$) is <0.5, whereas dissolution (σ_{pH}; Equation (2)) is indicated by values <0.25.

$$\sigma_{pH} = \sqrt{\frac{\sum_{i=1}^{8}(pH_i - pH_{1-8})^2}{8}} \quad (2)$$

Table 3. Compilation of R_{64d} for resins R1 and R4 (batch 1: from [20]; batch 2: this study).

Leaching Medium	Cumulative Release R_{64d}					
	R1		R4			
	BPA	BPF	BPA		BPF	
	mg/m²					
DW	batch 1		batch 1	batch 2	batch 1	batch 2
	0.045	<0.0002	0.021	0.073	0.0012	0.0021
GW1	batch 2		–			
	0.256	0.0005				
GW2 [1]	batch 2		batch 2			
	0.412	<0.0002	0.131		0.0011	
TW	batch 2		–			
	0.255	0.0006				

Note: [1]: A second batch of groundwater 2 (GW2*) was provided for leaching tests with resin R4.

Table 4. Root mean square error ($\sqrt{MSE}$) of BPA and BPF release from sewer renovation resins R1 and R4 with evaluation according to EN 16637-2:2023.

Resin System	Batch	Leaching Medium	$\sqrt{MSE}$ (BPA)	Diffusion	$\sqrt{MSE}$ (BPF)	Diffusion
R1	1	DW	0.59	–	-	-
R1	2	GW1	0.39	+	0.87	-
R1	2	GW2	0.87	–	-	-
R1	2	TW	0.25	+	0.29	+
R4	1	DW	1.17	–	1.06	-
R4	2	DW	0.25	+	0.95	-
R4	2	GW2 [1]	0.40	–	0.67	-

Note: [1]: A second batch of groundwater 2 (GW2*) was provided for leaching tests with resin R4.

The standardized dynamic surface leaching test (DSLT) enables the comparison of cumulative BPA, BPF, and DOC releases across different leaching media, including deionized water and natural waters, at room temperature (20 °C) over a period of 64 days. The statistical analysis presented here is exploratory due to the limited number of natural waters investigated. Leaching experiments conducted with resin systems R1 and R4 using natural leaching media yielded a coefficient of variation of 37.84% for the cumulative BPA release in the DSLT. As shown in Table 6, the relative variability of cumulative DOC, BPA, and BPF releases decreases as the number of natural waters included in the analysis increases. For the statistical evaluation, DOC and BPF concentrations below the limit of quantification (LOQ) were set equal to the LOQ. When all leaching media, including deionized water (DW), were considered, the coefficient of variation for cumulative BPA release increased to 77.47% across different resin systems (epoxy and vinyl ester resins) and batches. This

finding underscores the importance of considering different leaching media when assessing BPA release using the standardized DSLT. In contrast, when only deionized water was used as the leaching medium, the coefficient of variation for BPA release from epoxy and vinyl ester resin systems was 28.16% [20].

Table 5. Release mechanisms from sewer renovation products R1 and R4 according to the criteria of standard EN 16637-2:2023.

Resin System	Batch	Leaching Medium	$pH_1 - pH_{2\text{-}8}$	σ_{pH}	Surface Leaching/Dissolution
R1	1	DW	0.21	0.12	+/+
R1	2	GW1	0.21	0.09	+/+
R1	2	GW2	0.31	0.14	+/+
R1	2	TW	0.81	0.36	−/−
R4	1	DW	0.30	0.29	+/−
R4	2	DW	0.36	0.22	+/+
R4	2	GW2 [1]	0.37	0.16	+/+

Note: [1]: A second batch of groundwater 2 (GW2*) was provided for leaching tests with resin R4.

Table 6. Statistical analysis of sewer renovation products with a sample age of seven days (epoxy resin R1 and vinyl ester resin R4).

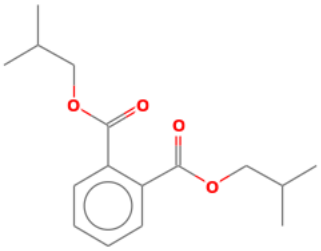
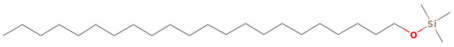
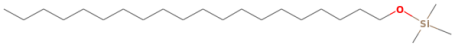
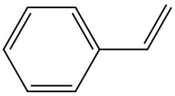
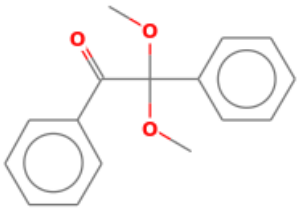
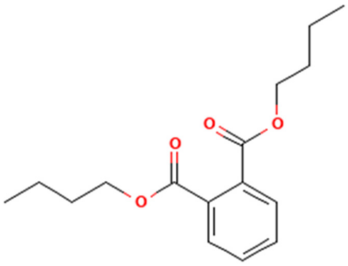
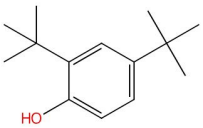
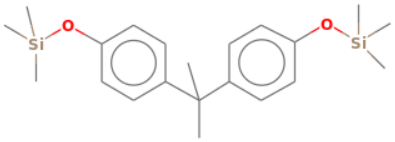
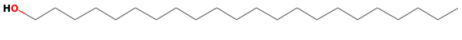
Parameter	Comparison of the Cumulative Releases R_{64d}								
	Groundwater 2 [1]			All Natural Water (GW1,GW2 [1] and TW)			Every Leaching Medium (DW, GW1,GW2 [1] and TW)		
	n = 2			n = 4			n = 7		
	Batch R1	Batch R4		Batch R1	Batch R4		Batch R1	Batch R4	
	2	2		2	2		1 and 2	1 and 2	
	Mean	SD	CV [2]	Mean	SD	CV	Mean	SD	CV
	mg/m^2		%	mg/m^2		%	mg/m^2		%
DOC	431	129	29.93	434	91	20.97	321	148	46.11
BPA	0.2715	0.1405	51.75	0.2635	0.0997	37.84	0.1704	0.1320	77.47
BPF	0.0007	0.0005	71.43	0.0006	0.0003	50.00	0.0008	0.0006	75.00

Notes: [1]: A second batch of groundwater 2 (GW2*) was provided for leaching tests with resin R4. [2]: CV shows the variance of the cumulative release in %.

3.6. GC-MS Screening on Eluates from Vinyl Ester Resin R4

To identify and evaluate additional substances with potential ecological or water-polluting effects in the eluates obtained from the leaching tests, GC/MS screening was performed on eluates from resin system R4. A semi-quantitative screening analysis, following the procedure described in [46], was conducted on eluates from the first and seventh sampling intervals using both leaching media, deionized water (DW) and groundwater GW2*. The substances identified in the eluates from both leaching media are listed in Table 7 together with their structural formulas. Quantitative concentration data for the substances detected in the DW and GW2* eluates are provided in the Supporting Information (Tables S2 and S3). Table 8 provides an overview of the substances identified by GC–MS screening, along with their concentration ranges in the two aforementioned leaching media.

Table 7. Detected substances in eluates from the first and seventh samplings following leaching of sewer rehabilitation product R4 using DW and GW2*, as identified by semi- quantitative GC/MS screening.

Compound	CAS No.	Substance Group	Structural Formula
1,2-Benzenedicarboxylic acid, bis(2-methylpropyl) ester	84-69-5	Phthalate esters	
Docosanol, TMS derivative	42449-18-3	aliphatic alcohol	
1-Eicosanol, TMS derivative	1000351-88-2	Arachidyl alcohol	
Styrene	100-42-5	Aromatic hydrocarbon	
Benzil dimethyl acetal	24650-42-8	Acetal	
Dibutyl phthalate	84-74-2	Phthalates	
2,4-Di-tert-butylphenol	96-76-4	Phenols	
1-Tricosene	18835-32-0	Alkene	
Bisphenol A, 2TMS derivative	4387-16-0	Siloxanes	
Behenic alcohol	661-19-8	fatty alcohols	

Styrene was detected in eluates from the vinyl ester resin R4 obtained using deionized water at a concentration of 13 µg/L in [20]. In the present study, styrene was also released from R4 resin discs, with higher concentrations observed when demineralized water was used as the leaching medium (49 µg/L, seventh sampling interval). In contrast to the GC–MS results reported in [20], tetrahydro-4-methyl-2H-pyran-2-one was not detected in any eluates obtained from leaching experiments using either deionized water or natural

waters. When groundwater GW2* was used as the leaching medium, several additional silicon-containing compounds were detected, consistent with the elevated silicon concentration measured in GW2* by ICP analysis. These compounds included docosanol (TMS derivative, $C_{25}H_{54}OSi$), 1-eicosanol (TMS derivative, $C_{23}H_{50}OSi$), and the bisphenol A-2TMS derivative ($C_{21}H_{32}O_2Si_2$). All of these compounds were present at concentrations below 1 µg/L and were not detected in the corresponding blank sample. Their occurrence may be attributed to the silicon content of the groundwater or, alternatively, to minor contamination from silicon residues on the borosilicate glass Petri dishes used for the fabrication of the vinyl ester R4 resin discs.

Table 8. Identified substances and hazard classifications for resin system R4 based on data from GESTIS (German Hazardous Substance Information System) [49] and the European Chemicals Agency (ECHA) [50].

Compound	Concentration Range of Semi-Quantitative Analyzes in µg/L	Selected Information from [49,50]
1,2-Benzenedicarboxylic acid, bis(2-methylpropyl) ester	0.4–2.8	– acute or chronic health risks – highly hazardous to water
Docosanol, TMS derivative	0.5–1.4	– No classification yet
1-Eicosanol, TMS derivative	0.3–1.2	– No classifications yet
Styrene	32.0–49.0	– Risk of reproductive toxicity suspected clearly – hazardous to water
Benzil dimethyl acetal	10.0–13.0	– acute or chronic health risks – hazardous to water
Dibutyl phthalate	0.078–0.73	– highly hazardous to water
2,4-Di-tert-butylphenol	0.49–0.53	– acute or chronic health risks – highly hazardous to water
1-Tricosene	0.17–0.36	– highly hazardous to water
Bisphenol A, 2TMS derivative	0.11–0.62	– No classifications yet
Behenic alcohol	0.19	– very toxic to aquatic life – acute health risks

3.7. Umu-Test Results for Eluates from Resin System R4

To determine the genotoxic potential of eluates obtained from leaching tests with deionized water or groundwater from the R4 resin system, the Umu test was performed according to DIN 38415-3 (T3): 1996-12 [48]. Eluates from the first and seventh sampling intervals were selected for this analysis. According to EN 16637-2:2023, the first eluate fraction, collected after 0.25 days (6 h), may represent the maximum concentration of critical components if surface wash-off is the dominant release mechanism. The seventh eluate fraction, collected after 36 days, likely contains the maximum concentration of critical components if diffusion is the dominant leaching mechanism [22], which is considered the case for R4.

The Umu test is a bacterial assay used to assess the genotoxic effects of chemical substances and complex mixtures. The vinyl ester resin system R4 showed the highest estrogenic activity in [20], corresponding to 0.47 ng EEQ/L using the ERα-CALUX method,

and was therefore selected for this investigation in accordance with the testing requirements of the DIBt [44]. The eluates obtained with both leaching media, deionized water and groundwater (GW2*), showed induction rates below 1.5 (G_{EU}), indicating that no genotoxic effects were detected under the investigated conditions according to the evaluation criteria described in [48] (Table 9).

Table 9. Genotoxicity results of eluates from sewer rehabilitation product R4.

Removal	Induction Rate in the Umu-Test	
	Deionized Water	Groundwater GW2*
1st (after 6 h)	1.5	1.5
7th (after 36 d)	1.5	1.5

4. Discussion

This study investigated only three natural waters and two resin systems used for sewer rehabilitation. Consequently, the observed relationships between water chemistry and BPA release should be regarded as preliminary and require validation using a broader range of water types and resin formulations. Elevated pH and water hardness have previously been reported to increase BPA release [51]. Among the investigated parameters, pH exhibited the strongest apparent association with BPA release. However, the limited number of leaching media investigated does not allow for robust statistical conclusions. The analysis was based on four leaching media (deionized water, GW1, GW2, and tap water). For epoxy resin system R1, cumulative BPA release tended to increase with the mean pH of the DSLT eluates ($R^2 = 0.79$, n = 4). Based on this exploratory relationship, Equation (3) was derived to estimate cumulative BPA release from the mean eluate pH.

$$\text{Cumulative BPA} - \text{release(R1)}\left(\frac{\text{mg}}{\text{m}^2}\right) \approx -0.6406 + 0.1176 \times \text{pH} \quad (3)$$

Although the calculated values were in reasonable agreement with the measured releases (Table 10), the limited dataset precludes mechanistic conclusions.

Table 10. Comparison of measured and calculated cumulative BPA releases in the DSLT (R1).

Resin System	Leaching Medium	BPA_{64d} Release in mg/m^2 (Experiment)	BPA_{64d} Release in mg/m^2 (Calculated)
R1	DW [20]	0.045	0.041
R1	GW1	0.256	0.294
R1	GW2	0.412	0.318
R1	TW	0.255	0.315

Table 11 provides an overview of correlations between the parameters measured in this study and BPA release. Pearson correlation coefficients (r) are provided for exploratory purposes only. Due to the limited dataset, statistical power is low, and *p*-values should not be interpreted as confirmatory tests of statistical significance.

The use of groundwater or tap water substantially increased BPA release compared with deionized water. For resin system R1, cumulative BPA release increased by factors of 5.7–9.2 and exceeded the release limit of 0.085 mg/m^2 derived from the EQS insignificance threshold of 1.7×10^{-4} µg/L using the model approach described in [23]. In contrast, the WHO precautionary value for aquatic organisms of 0.01 µg/L [52] corresponds to a cumulative release of 5.02 mg/m^2 in the DSLT and was met by all resin systems tested with natural waters. The ECHA-referenced maximum allowable migration (MAM) of 2.5 µg/L for BPA

in drinking water is not suitable for deriving a cumulative allowable release in the dynamic surface leaching test (DSLT) according to EN 16637-2. The MAM is intended to limit migration from drinking water contact materials under defined conditions and does not represent a cumulative leaching criterion applicable to the DSLT. The findings indicate that the use of deionized water in the standardized DSLT may underestimate environmentally relevant emissions from sewer rehabilitation products. The release mechanisms identified according to EN 16637-2:2023 varied among resin systems and leaching media. Diffusion-controlled BPA release was observed for R1 in GW1 and tap water and for the second batch of R4 in deionized water. Surface leaching and dissolution criteria were fulfilled in most test configurations (Tables 4 and 5), indicating that multiple release processes contribute to BPA and BPF emissions. No uniform release mechanism was observed across all systems. The release-mechanism classification was applied according to [22], although the applicability of these criteria to organic monomers such as BPA and BPF remains insufficiently validated.

Table 11. Correlations of parameters with cumulative BPA releases in the DSLT (resin R1).

Parameter		R^2 with BPA (Cumulative Release, mg/m^2)	Pearson r	*p* Value (Two-Tailed)
pH	Mean eluate pH	0.79	0.89	0.106
El. conductivity	Mean eluate conductivity	0.40	0.63	0.423
Hardness	Blank value	0.50	0.71	0.333
Calcium	Blank value	0.54	0.74	0.303
Sulfate	Blank value	0.18	0.42	0.637

Electrical conductivity and DOC concentrations frequently decreased below the corresponding blank values during later leaching intervals, suggesting interactions between dissolved constituents and the resin surface. Low DOC concentrations in the eluates may indicate initial adsorption to the resin surface followed by delayed release, without substantially affecting diffusion behavior (Table 4). The highest DOC concentration and BPA concentration (1.1 µg/L) were observed in the seventh eluate obtained from GW2* and the second batch of R4, consistent with near-diffusion-controlled release (RMSE = 0.40) of this monomer in combination with surface leaching and dissolution. BPA adsorption is known to depend on pH, dissolved organic matter, and ionic composition [35,53–64]. Under alkaline conditions, BPA occurs predominantly in its dissociated form [54], enabling interactions with divalent cations such as Ca^{2+} through ion-bridge formation [35,60–64]. Because calcium was the dominant cation in the investigated natural waters, such interactions may have influenced BPA partitioning between the resin surface and the aqueous phase. However, adsorption processes were not directly investigated in this study and should therefore be regarded as a hypothesis requiring dedicated experimental verification.

GC–MS screening identified several organic compounds in eluates from the vinyl ester resin R4, including styrene, benzil dimethyl acetal, dibutyl phthalate, 2,4-di-tert-butylphenol, and long-chain alcohols. Chlorinated phenolic transformation products were not detected [28–33]. Styrene showed the highest concentrations (32–49 µg/L), whereas 2,4-di-tert-butylphenol was detected only at low concentrations (≤0.53 µg/L), considerably below those previously observed for epoxy resin systems [20]. Several detected compounds are classified as hazardous to aquatic environments or are associated with adverse health effects [50,51], indicating that the environmental assessment of sewer rehabilitation materials should not be limited to BPA and BPF alone. Styrene concentrations exceeded those of BPA by approximately one order of magnitude. Despite the presence of BPA,

BPF, styrene, and other organic substances, no genotoxic effects were detected in the Umu test. Furthermore, all compounds identified by GC–MS screening were predicted to be non-mutagenic using the VEGA QSAR Ames model. Nevertheless, endocrine activity and mixture effects cannot be excluded and should be assessed using complementary ecotoxicological endpoints [65–74].

Overall, the results demonstrate that environmentally relevant water chemistry can significantly influence BPA and BPF release from sewer rehabilitation resins. Future studies should include a wider range of natural and synthetic waters to disentangle the effects of pH, ionic strength, hardness, and dissolved organic matter, thereby improving environmental exposure assessments for polymer-based sewer rehabilitation products.

Table 12 shows the key factors affecting BPA and BPF release from sewer rehabilitation resin systems and summarizes their implications for environmental assessment, including the influence of resin formulation, water chemistry, and release mechanisms.

Table 12. Key factors influencing bisphenol release from sewer rehabilitation resin systems.

Factor	Relevance for Sewer Rehabilitation Resin Systems	Implications for Environmental Assessment
BPA and BPF release from resin systems	Residual monomers and bisphenol compounds may migrate from cured epoxy and vinyl ester resins into contacting water	Bisphenol release represents a potential environmental exposure pathway requiring consideration in risk assessments
Influence of water chemistry	pH, hardness, ionic strength, and dissolved organic carbon can affect BPA/BPF mobility, adsorption, and partitioning	Testing with deionized water may not fully represent environmentally relevant release conditions
Multiple release mechanisms	Diffusion, surface wash-off, dissolution, and interactions with dissolved constituents may contribute to overall release	Resin-specific evaluation is needed to describe release behavior adequately
Limitations of current assessment approaches	Standard test conditions may not capture the influence of natural water chemistry and long-term release processes	More realistic leaching scenarios are needed for improved environmental risk assessment

5. Conclusions

This study demonstrates that the choice of leaching medium significantly affects the measured BPA and BPF release from sewer rehabilitation resins in the standardized DSLT. Compared with deionized water, environmentally relevant waters, such as groundwaters and tap water, resulted in substantially higher BPA release, exceeding the values obtained under standard test conditions. This indicates that the use of deionized water as the leaching medium may underestimate cumulative BPA release from sewer rehabilitation resins by up to one order of magnitude. Despite the increased BPA release from resin systems used in sewer rehabilitation products, all tested eluates showed no genotoxic effects under the applied test conditions. These results highlight the importance of incorporating environmentally realistic water chemistries into leaching assessments for polymer-based construction materials. Future work should expand the range of water chemistries and resin formulations investigated to improve predictive understanding and support more robust environmental risk assessment frameworks.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w18162021/s1, Table S1: Concentrations in eluates using resin system R4 (7d sample age) according to EN 16637-2 [22] of chloride (Cl^-), sulfate (SO_4^{2-}), calcium (Ca^{2+}), sodium (Na^+), bisphenol A (BPA) and bisphenol F (BPF). Table S2: Results of the GC-MS screening of eluates from the first and seventh sampling after leaching from sewer rehabilitation product R4 using deionized water. Table S3: Results of the GC-MS screening of eluates from the first and seventh sampling after leaching from sewer rehabilitation product R4 using GW2 (batch 2).

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References

1. Tscheikner-Gratl, F.; Caradot, N.; Cherqui, F.; Leitão, J.P.; Ahmadi, M.; Langeveld, J.G.; Le Gat, Y.; Scholten, L.; Roghani, B.; Rodríguez, J.P.; et al. Sewer asset management—State of the art and research needs. *Urban Water J.* **2019**, *16*, 662–675. [CrossRef]
2. VanDerslice, J. Drinking water infrastructure and environmental disparities: Evidence and methodological considerations. *Am. J. Public Health* **2011**, *101*, S109–S114. [CrossRef] [PubMed]
3. Fenner, R.A. Approaches to sewer maintenance: A review. *Urban Water* **2000**, *2*, 343–356. [CrossRef]
4. Alyami, S.H.; Abd El Aal, A.K.; Alqahtany, A.; Aldossary, N.A.; Jamil, R.; Almohassen, A.; Alzenifeer, B.M.; Kamh, H.M.; Fenais, A.S.; Alsalem, A.H. Developing a Holistic Resilience Framework for Critical Infrastructure Networks of Buildings and Communities in Saudi Arabia. *Buildings* **2023**, *13*, 179. [CrossRef]
5. Duque, N.; Scholten, L.; Maurer, M. Exploring transitions of sewer wastewater infrastructure towards decentralisation using the modular model TURN-Sewers. *Water Res.* **2024**, *257*, 121640. [CrossRef] [PubMed]
6. RSV (Rohrleitungssanierungsverband). *RSV—Leaflet 1.1, Renovation of Sewers and Pipes with In-Situ Curing Pipe Lining*; RSV: Hamburg, Germany, 2021. Available online: www.RSV-EV.de (accessed on 29 May 2026).
7. Ji, H.W.; Koo, D.D.; Kang, J.H. Short- and Long-Term Structural Characterization of Cured-in-Place Pipe Liner with Reinforced Glass Fiber Material. *Int. J. Environ. Res. Public Health* **2020**, *17*, 2073. [CrossRef] [PubMed]
8. Jiang, D.; Chen, W.-Q.; Zeng, X.; Tang, L. Dynamic Stocks and Flows Analysis of Bisphenol A (BPA) in China: 2000–2014. *Environ. Sci. Technol.* **2018**, *52*, 3706–3715. [CrossRef] [PubMed]
9. Available online: https://echa.europa.eu/de/ed-assessment (accessed on 30 May 2026).
10. European Chemical Agency. *Restriction of the Use of Two-Component Epoxy Based on Bisphenol A in Relining of Tap Water Pipes*; European Chemical Agency: Helsinki, Finland, 2015.
11. European Chemical Agency. *European Positive List of the Drinking Water Directive. Article 11 of Directive (EU) 2020/2184 (DWD), Annex I, European Positive List of Organic Constituents for Cementitious Materials*; European Chemical Agency: Helsinki, Finland, 2024.
12. Gimeno, S.; Gerritsen, A.; Bowmer, T.; Komen, H. Feminization of male carp. *Nature* **1996**, *384*, 221–222. [CrossRef] [PubMed]
13. UBA (Umweltbundesamt). *Bisphenol A, an Industrial Chemical with Adverse Effects*; Federal Environment Agency: Washington, DC, USA, 2010. [CrossRef]
14. Jašarević, E.; Sieli, P.T.; Twellman, E.E.; Welsh, T.H.; Schachtman, T.R.; Roberts, R.M.; Geary, D.C.; Rosenfeld, C.S. Disruption of adult expression of sexually selected traits by developmental exposure to bisphenol A. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 11715–11720. [CrossRef] [PubMed]

15. Qiua, W.; Zhanc, H.; Hua, J.; Zhanga, T.; Xud, H.; Wonga, M.; Xuf, B.; Zhenga, C. The occurrence, potential toxicity, and toxicity mechanism of bisphenol S, a substitute of bisphenol A: A critical review of recent progress. *Ecotoxicol. Environ. Saf.* **2019**, *173*, 192–202. [CrossRef] [PubMed]
16. Adamovsky, O.; Groh, K.J.; Białk-Bielinska, A.; Escher, B.I.; Beaudouin, R.; Lagares, L.M.; Tollefsen, K.E.; Fenske, M.; Mulkiewicz, E.; Creusot, N.; et al. Exploring BPA alternatives—Environmental levels and toxicity review. *Environ. Int.* **2024**, *189*, 108728. [CrossRef] [PubMed]
17. International Chemical Secretariat. *Bisphenol A in Relining of Water Pipes*; International Chemical Secretariat: Göteborg, Sweden, 2011.
18. Bruchet, A.; Elyasmino, N.; Decottignies, V.; Noyon, N. Leaching of bisphenol A and F from new and old epoxy coatings: Laboratory and field studies. *Water Sci. Technol. Water Supply* **2014**, *14*, 383–389. [CrossRef]
19. Rajasärkkä, J.; Pernica, M.; Kuta, J.; Lasnak, J.; Simek, Z.; Blaha, L. Drinking water contaminants from epoxy resin-coated pipes: A field study. *Water Res.* **2016**, *103*, 133–140. [CrossRef] [PubMed]
20. Ahrens, K.; Gschwendtner, R.; Linnemann, V.; Vollpracht, A. Bisphenol A leaching from sewer renovation products. *Environ. Chall.* **2025**, *21*, 101342. [CrossRef]
21. Maćczak, A.; Cyrkler, M.; Bukowska, B.; Michałowicz, J. Bisphenol A, bisphenol S, bisphenol F and bisphenol AF induce different oxidative stress and damage in human red blood cells (in vitro study). *Toxicol. Vitr.* **2017**, *41*, 143–149. [CrossRef] [PubMed]
22. *EN 16637-2*; Construction Products—Assessment of Release of Dangerous Substances—Part 2: Horizontal Dynamic Surface Leaching Test. European Committee for Standardization (CEN): Brussels, Belgium, 2023.
23. Brameshuber, W.; Vollpracht, A. *Assessment of the Environmental Compatibility of Sealing and Injection Materials*; Fraunhofer IRB Verlag (Bauforschung T 3256); Research Report No. F 7039; Institute for Building Research, RWTH Aachen University: Aachen, Germany, 2011.
24. German Federal Ministry for the Environment; Nature Conservation; Nuclear Safety and Consumer Protection (BMUV); German Federal Environment Agency (UBA). *The Water Framework Directive—Waters in Germany 2021*; German Federal Environment Agency: Dessau-Roßlau, Germany, 2022. Available online: www.umweltbundesamt.de/publikationen (accessed on 30 May 2026).
25. Viñas, R.; Goldblum, R.M.; Watson, C.S. Rapid Estrogenic Signaling Activities of the Modified (chlorinated, Sulfonated, and Glucuronidated) Endocrine Disruptor Bisphenol A. *Endocr. Disruptors* **2013**, *1*, e25411. [CrossRef]
26. Ho, K.L.; Yuen, K.K.; Yau, M.S.; Murphy, M.B.; Wan, Y.; Fong, B.M.W.; Tam, S.; Giesy, J.P.; Leung, K.S.Y.; Lam, M.H.W. Glucuronide and Sulfate Conjugates of Bisphenol A: Chemical Systhesis and Correlation Between Their Urinary Levels and Plasma Bisphenol A Content in Voluntary Human Donors. *Arch. Environ. Contam. Toxicol.* **2017**, *73*, 410–420. [CrossRef] [PubMed]
27. Shimizu, M.; Ohta, K.; Matsumoto, Y.; Fukuoka, M.; Ohno, Y.; Ozawa, S. Sulfation of bisphenol A abolished its estrogenicity based on proliferation and gene expression in human breast cander MCF-7 cells. *Toxicol. Vitr.* **2002**, *16*, 549–556. [CrossRef] [PubMed]
28. Gallard, H.; Leclercq, A.; Croué, J.P. Chlorination of Bisphenol A: Kinetics and by-products formation. *Chemosphere* **2004**, *56*, 465–473. [CrossRef] [PubMed]
29. Lane, R.F.; Adams, C.D.; Randtke, S.J.; Carter, R.E., Jr. Chlorination and chloramination of bisphenol A, bisphenol F, and bisphenol A diglycidyl ether in drinking water. *Water Res.* **2015**, *79*, 68–78. [CrossRef] [PubMed]
30. Hu, J.Y.; Aizawa, T.; Ookubo, S. Products of aqueous chlorination of bisphenol A and their estrogenic activity. *Environ. Sci. Technol.* **2002**, *36*, 1980–1987. [CrossRef] [PubMed]
31. Yamamoto, T.; Yasuhara, A. Chlorination of bisphenol A in aqueous media: Formation of chlorinated bisphenol A congeners and degradation to chlorinated phenolic compounds. *Chemosphere* **2002**, *46*, 1215–1223. [CrossRef] [PubMed]
32. Fan, Z.; Hu, J.; An, W.; Yang, M. Detection and occurrence of chlorinated byproducts of bisphenol a, nonylphenol, and estrogens in drinking water of china: Comparison to the parent compounds. *Environ. Sci. Technol.* **2013**, *47*, 10841–10850. [CrossRef] [PubMed]
33. Kosaka, K.; Hayashida, T.; Terasaki, M.; Asami, M.; Yamada, T.; Itoh, M.; Akiba, M. Elution of bisphenol A and its chlorination by-products from lined pipes in water supply process. *Water Sci. Technol. Water Supply* **2012**, *12*, 791–798. [CrossRef]
34. Gerona, R.R.; Woodruff, T.J.; Dickenson, C.A.; Pan, J.; Schwartz, J.M.; Sen, S.; Friesen, M.M.; Fujimoto, V.Y.; Hunt, P.A. Bisphenol-A (BPA), BPA glucuronide, and BPA sulfate in midgestation umbilical cord serum in a Northern and Central California population. *Environ. Sci. Technol.* **2013**, *47*, 12477–12485. [CrossRef] [PubMed]
35. Sun, W.L.; Ni, J.R.; O'Brien, K.C.; Hao, P.P.; Sun, L.Y. Adsorption of bisphenol A on sediments in the yellow river. *Water Air Soil Pollut.* **2005**, *167*, 353–364. [CrossRef]
36. *ISO 10523:2008-12*; Water Quality—Determination of pH. International Organization for Standardization: Geneva, Switzerland, 2008.
37. *ISO 7888:1985-05*; Water Quality—Determination of Electrical Conductivity. International Organization for Standardization: Geneva, Switzerland, 1985.
38. *DIN 38406-3:2002-03*; German Standard Methods for the Examination of Water, Waste Water and Sludge—Cations (Group E)—Part 3: Determination of Calcium and Magnesium, Complexometric Method (E 3). Beuth Verlag GmbH: Berlin, Germany, 2002.

39. *ISO 11885:2007*; Water Quality—Determination of Selected Elements by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). International Organization for Standardization: Geneva, Switzerland, 2007.
40. *ISO 17294-1:2024*; Water Quality—Application of Inductively Coupled Plasma Mass Spectrometry (ICP-MS)—Part 1: General Requirements. International Organization for Standardization: Geneva, Switzerland, 2024.
41. *ISO 18857-2:2009-09*; Water Quality—Determination of Selected Alkylphenols—Part 2: Gas Chromatographic-Mass Spectrometric Determination of Alkylphenols, Their Ethoxylates and Bisphenol A in Non-Filtered Samples Following Solid-Phase Extraction and Derivatisation. International Organization for Standardization: Geneva, Switzerland, 2009.
42. *DIN EN ISO 7393-2:2019-03*; Water Quality—Determination of Free Chlorine and Total Chlorine. Beuth Verlag GmbH: Berlin, Germany, 2019.
43. NIST Public Data Repository. *NIST Inorganic Crystal Structure Database, NIST Standard Reference Database Number 3*; National Institute of Standards and Technology: Gaithersburg, MD, USA, 2018. [CrossRef]
44. German Institute for Building Technology. *Testing Requirements for the "PAA-F-Liner" Pipe Lining Method for Sewer Rehabilitation*; German Institute for Building Technology: Berlin, Germany, 2025.
45. Staples, C.A.; Dom, P.B.; Klecka, G.M.; O'Block, S.T.; Harris, L.R. A review of the environmental fate, effects, and exposures of bisphenol A. *Chemosphere* **1998**, *36*, 2149–2173. [CrossRef] [PubMed]
46. *DIN 3599:2022-02*; Solid—GC-MS-Screening—Qualitative and Semi-Quantitative Screening Analysis. Beuth Verlag GmbH: Berlin, Germany, 2022.
47. Oda, Y.; Nakamura, S.; Oki, I.; Kato, T.; Shinagawa, H. Evaluation of the new system (umu-test) for the detection of environmental mutagens and carcinogens. *Mutat. Res.* **1985**, *147*, 219–229. [CrossRef] [PubMed]
48. *DIN 38415-T3:1996-12*; German Standard Methods for the Examination of Water, Waste Water and Sludge—Sub-Animal Testing (Group T)—Part 3: Determination of the Genotype Potential of Water and Waste Water Components with the Umu-Test (T 3). Beuth Verlag GmbH: Berlin, Germany, 1996.
49. Institute for Occupational Safety and Health of the German Social Accident Insurance. GESTIS- Substance Database. Available online: https://gestis.dguv.de/ (accessed on 30 May 2026).
50. ECHA. European Chemicals Agency. Available online: https://echa.europa.eu/de/information-on-chemicals (accessed on 30 May 2026).
51. Biedermann-Brem, S.; Grob, K. Release of bisphenol A from polycarbonate baby bottles: Water hardness as the most relevant factor, Original paper. *Eur. Food Res. Technol.* **2009**, *228*, 679–684. [CrossRef]
52. EP (European Parliament). The European Parliament and the Council of the European Union Report on the Proposal for a Directive of the European Parliament and of the Council on the Quality of Water Intended for Human Consumption (Recast), Report A8-0288/2018. 2018. Available online: https://www.europarl.europa.eu/doceo/document/A-8-2018-0288_EN.html (accessed on 30 May 2026).
53. Cheng, F.; Wang, J. Removal of bisphenol a from wastewater by adsorption and membrane separation: Performances and mechanisms. *Chem. Eng. J.* **2024**, *484*, 149414. [CrossRef]
54. Rojas, S.; Horcajada, P. Metal–organic frameworks for the removal of emerging organic contaminants in water. *Chem. Rev.* **2020**, *120*, 8378–8415. [CrossRef] [PubMed]
55. Tran, H.N.; You, S.-J.; Chao, H.P. Fast and efficient adsorption of methylene green 5 on activated carbon prepared from new chemical activation method. *J. Environ. Manag.* **2017**, *188*, 322–336. [CrossRef] [PubMed]
56. Mpatani, F.M.; Han, R.; Aryee, A.A.; Kani, A.N.; Li, Z.; Qu, L. Adsorption performance of modified agricultural waste materials for removal of emerging microcontaminant bisphenol A: A comprehensive review. *Sci. Total Environ.* **2021**, *780*, 146629. [CrossRef] [PubMed]
57. Ali, I.; Gupta, V.K. Advances in water treatment by adsorption technology. *Nat. Protoc.* **2006**, *1*, 2661–2667. [CrossRef] [PubMed]
58. Dong, Y.; Wu, D.; Chen, X.; Lin, Y. Adsorption of bisphenol A from water by surfactant-modified zeolite. *J. Colloid Interface Sci.* **2010**, *348*, 585–590. [CrossRef] [PubMed]
59. Enyojo, T.B.; Oluwasogo, D.A.; Abosede, I.A.; Shola, O.K.; Solomon, B.O.; Ujjwal, P. Agro-waste based adsorbents as sustainable materials for effective adsorption of Bisphenol A from the environment: A review. *J. Clean. Prod.* **2023**, *388*, 135819. [CrossRef]
60. Guo, F.; Li, D.; Fein, J.B.; Xu, J.; Wang, Y.; Huang, Q.; Rong, X. Roles of hydrogen bond and ion bridge in adsorption of two bisphenols onto montmorillonite: An experimental and DFT study. *Appl. Clay Sci.* **2022**, *217*, 106406. [CrossRef]
61. Bekbölet, M.; Yenigün, O.; Yücel, I. Sorption studies of 2,4-D on selected soils. *Water Air Soil Pollut.* **1998**, *111*, 75–88. [CrossRef]
62. Barriuso, E.; Baer, U.; Calvet, R. Dissolved Organic Matter and Adsorption-Desorption of Dimefuron, Atrazine, and Carbetamide by Soils. *J. Environ. Qual.* **1992**, *21*, 359–367. [CrossRef]
63. Spark, K.M.; Swift, R.S. Effect of soil composition and dissolved organic matter on pesticide sorption. *Sci. Total Environ.* **2002**, *298*, 147–161. [CrossRef] [PubMed]
64. Xie, H.; Wu, J.; Yu, M.; Yan, H.; Masum, S.; Cai, P.; Chen, Y. Bisphenol A adsorption and transport in loess and cationic surfactant/hydrophilic polymer modified bentonite liners. *J. Environ. Manag.* **2023**, *336*, 117604. [CrossRef] [PubMed]

65. Huang, Y.; Li, W.; Qin, L.; Xie, X.; Gao, B.; Sun, J.; Li, A. Distribution of endocrine-disrupting chemicals in colloidal and soluble phases in municipal secondary effluents and their removal by different advanced treatment processes. *Chemosphere* **2019**, *219*, 730–739. [CrossRef] [PubMed]
66. Zhao, F.; Wang, P.; Lucardi, R.D.; Su, Z.; Li, S. Natural Sources and Bioactivities of 2,4-Di-Tert-Butylphenol and Its Analogs. *Toxins* **2020**, *12*, 35. [CrossRef] [PubMed]
67. *EN ISO 8692:2012*; Water Quality—Fresh Water Algal Growth Inhibition Test with Unicellular Green Algae (ISO 8692:2012), German Version. International Organization for Standardization: Geneva, Switzerland, 2012.
68. *EN ISO 20079:2006*; Water Quality—Determination of the Toxic Effect of Water Constituents and Waste Water on Duckweed (Lemna Minor)—Duckweed Growth Inhibition Test (ISO 20079:2005), German Version. International Organization for Standardization: Geneva, Switzerland, 2006.
69. *EN ISO 6341:2012*; Water Quality—Determination of the Inhibition of the Mobility of Daphnia Magna Straus (Cladocera, Crustacea)—Acute Toxicity Test (ISO 6341:2012), German Version. International Organization for Standardization: Geneva, Switzerland, 2012.
70. de Kermoysana, G.; Joachim, S.; Baudoin, P.; Lonjaret, M.; Tebby, C.; Lesaulnier, F.; Lestremau, F.; Chatellier, C.; Akrour, Z.; Pheron, E.; et al. Effects of bisphenol A on different trophic levels in a lotic experimental ecosystem. *Aquat. Toxicol.* **2013**, *144–145*, 186–198. [CrossRef] [PubMed]
71. Ferrer-Polonio, E.; Bretas Alvim, C.; Fernández-Navarro, J.; Mompó-Curell, R.; Mendoza-Roca, J.A.; Bes-Piá, A.; Alonso-Molina, J.L.; Amorós-Muñoz, I. Influence of bisphenol A occurrence in wastewaters on biomass characteristics and activated sludge process performance. *Sci. Total Environ.* **2021**, *778*, 146355. [CrossRef] [PubMed]
72. Czarny-Krzyminska, K.; Krawczyk, B.; Szczukocki, D. Bisphenol A and its substitutes in the aquatic environment: Occurrence and toxicity assessment. *Chemosphere* **2023**, *315*, 137763. [CrossRef] [PubMed]
73. Gao, Y.; Xiao, S.K.; Wu, Q.; Pan, C.G. Bisphenol analogues in water and sediment from the Beibu Gulf, South China Sea: Occurrence, partitioning and risk assessment. *Sci. Total Environ.* **2023**, *857*, 159445. [CrossRef] [PubMed]
74. Zhao, X.; Qiu, W.; Zheng, Y.; Xiong, J.; Gao, C.; Hu, S. Occurrence, distribution, bioaccumulation, and ecological risk of bisphenol analogues, parabens and their metabolites in the Pearl River Estuary, South China. *Ecotoxicol. Environ. Saf.* **2019**, *180*, 43–52. [CrossRef] [PubMed]

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