Evaluating the Hypothesis of Per- and Polyfluoroalkyl Substances (PFAS) Presence in HDPE Geomembranes

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## Highlights

- PFPrA was found in all examined geomembranes, with concentrations ranging from < limit of quantification (LOQ) to 0.44 μg/g.
- Higher methanol concentrations (100% methanol) improved extraction efficiency, yielding PFPrA levels up to 0.44 µg/g compared to 0.09 µg/g in 10% methanol solutions.
- PFPrA concentrations varied by production facility, with geomembrane 1 exhibiting levels about one order of magnitude higher than geomembranes 2 and 3
- Total fluorine measurements were consistently below LOQ, suggesting minimal presence of other PFAS than PFPrA.

Journal

# **Evaluating the Hypothesis of Per- and Polyfluoroalkyl Substances (PFAS) Presence in HDPE Geomembranes**

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#### Abstract

This study examines the presence of per- and polyfluoroalkyl substances (PFAS) in high-density polyethylene (HDPE) geomembranes, which are commonly utilised in waste containment facilities, hydraulic infrastructure and other engineering applications. Three different HDPE geomembranes (GMBs) were analysed for PFAS content using targeted detection of six specific analytes and total fluorine (TF) measurements. To assess PFAS leachability under different conditions, extraction experiments were conducted using solutions with varying methanol concentrations. The results showed that perfluoropropionic acid (PFPrA), an ultra-short-chain PFAS, was detected in all tested geomembranes at concentrations ranging from below the limit of quantification (LOQ) to 0.44 µg/g. Importantly, PFPrA concentrations in two geomembranes (GMB2 and GMB3) manufactured at the same facility were comparable, whereas GMB1, produced at a different plant, exhibited concentrations nearly an order of magnitude higher. This disparity suggests potential differences in polymer processing aid (PPA) formulations, PFAScontaining additives, or variations in manufacturing processes. TF measurements for all samples fell below the reporting limit, indicating that large quantities of other PFAS were unlikely to be present. However, the high limit of quantification (LOQ) of 5 mg/kg for TF analysis likely resulted in excessive data censoring, highlighting the need for more sensitive TF detection methods. As regulatory pressures drive a transition toward PFAS-free polymer processing aids, a significant issue may arise if unregulated or unknown PFAS substitutes are used in place of regulated or guideline-referenced PFAS chemicals. Future research should investigate a broader range of geomembrane types and PFAS analytes, enabling more generalised conclusions to be drawn regarding the presence of PFAS in geomembranes.

Keywords: Geomembranes, Geosynthetics, PFAS, PFPrA, Polymer Processing Aids,

#### 1. Introduction

High-density polyethylene (HDPE) geomembranes are widely used as hydraulic barriers in waste containment facilities and hydraulic structures such as dams and reservoirs, among many others (Jeon et al., 2008; Hornsey et al., 2010; Bouazza et al., 2014; Rowe et al., 2020; Rowe, 2020; Bouazza and Zhang, 2020; Cazuffi & Gioffre, 2020; Rowe & Fan, 2024). In waste containment, they help prevent leachates and contaminants from migrating into the surrounding soil and underlying groundwater. In hydraulic infrastructures, they serve to minimise water seepage, ensuring efficient water retention.

HDPE geomembranes are manufactured using polyethylene resins, a type of polyolefin, and polymer processing aids (PPAs) to enhance production efficiency (ATA, 2023). Furthermore, various additives such as pigments, plasticisers, fillers, and carbon black are often added to geomembranes to optimise their performance under diverse conditions (Scheirs, 2009). PPAs comprising fluoropolymers combined with non-polymeric fluorosurfactants have been traditionally employed to reduce pressure, melt fracture, machine torque and process temperature during the extrusion of polyolefins, resulting in higher output rates (Oriani, 2005).

Fluoropolymers and non-polymeric fluorosurfactants are two distinct subsets of per- and polyfluoroalkyl substances (PFAS) (Parsons et al., 2008; Buck et al., 2011). Fluoropolymers typically consist of a carbon-only polymer backbone with fluorine atoms directly attached, whereas fluorosurfactants, including perfluoroalkyl acids (PFAA), have a fluorinated hydrophobic and lipophilic segment connected to one or more hydrophilic and lipophobic functional groups. Due to their amphiphilic nature, low molecular polarity, and high thermal and chemical stability, PFAS are widely used in manufacturing textiles, plastics, rubber, fire-fighting foams, electroplating, and food packaging materials (Kannan et al., 2011; Glüge et al., 2022).

Widespread human exposure to PFAS in food, air, and water, combined with their long-term persistence, has led to ubiquitous environmental pollution, raising concerns about their potential adverse impacts on both wildlife and humans (Fenton et al., 2020). As a result, PFAS, specifically perfluorooctane sulfonic acid (PFOS), perfluorooctanoic acid (PFOA), and perfluorohexane sulfonic acid (PFHxS), as well as their salts and related compounds, were incorporated into the annexes of the Stockholm Convention (UNEP, 2009, 2019, 2022). However, new unregulated PFAS continue to emerge, often with unknown risks (Brunn et al., 2023). Guidelines and regulatory frameworks are rapidly evolving, with more PFAS being added to advisories and stricter limits on permissible concentrations (Health Canada, 2023; US EPA, 2024; NHMRC, 2024). In February 2023, the European Chemicals Agency (ECHA) proposed banning the production, import, and use of PFAS, including PFAS-based PPAs (ECHA, 2023). Since then, the geomembrane industry has faced growing regulatory scrutiny due to concerns about PFAS.

Publicly available information on the direct use of PFAS, including fluoropolymers and fluorosurfactants, in geomembrane manufacturing additives, such as pigments, carbon black, lubricants, mould release agents, and extrusion line purging compounds, is limited. However, PFAS are known to be present in various industrial additives, many of which are also used in geomembrane production processes, suggesting potential pathways for their unintentional inclusion. In HDPE geomembranes, pigments are commonly used to provide colour and UV stabilisation, with carbon black and titanium dioxide being the most frequently employed (Amtsberg et al., 2024). These pigments help control surface temperature and enhance the material's durability. However, achieving uniform pigment dispersion can be challenging, as it requires dispersants to integrate pigments into the geomembrane evenly. Some pigment

dispersions may contain PFAS to enhance this process (Gaines, 2023). Fluorosurfactants in these dispersions adsorb onto pigment surfaces, with their perfluoroalkyl groups facing the pigment and their functional groups oriented toward the dispersing medium. This alignment stabilises the dispersion, improving efficiency and effectiveness. Lubricants facilitate the release of metal during the calendering process. PFAS are sometimes added to lubricants due to their high thermal and chemical stability, nonreactivity, and low surface tension (Zhu and Kannan, 2020). PFAS are also used as mould-release agents to prevent resin adhesion and improve mould-release efficiency (Gaines, 2023). Additionally, purging compounds are used in extrusion to remove residual HDPE resin during product changeovers or after prolonged operation. These compounds help eliminate contaminants, ensuring a clean extruder for new resin. They typically contain fluoropolymer particles that are non-melt flowing at the temperature of the extruder's operation

Based on the known use of PFAS in PPAs and other industrial additives, as well as their potential application in geomembrane manufacturing processes, it can be inferred that PFAS may be employed to aid in geomembrane production. If not entirely removed during manufacturing, residues of these compounds may remain on the final product, potentially introducing PFAS into the environment. Furthermore, depending on the context of the application, PFAS in geomembranes could contribute to overall PFAS concentrations and increase environmental risks. For instance, in waste containment facilities, geosynthetic composite lining systems incorporating geomembranes may serve as additional sources of PFAS, potentially leading to elevated concentrations in landfill leachate. Currently, studies on the presence of PFAS in geomembrane liners, particularly in HDPE geomembranes, are scarce. However, a study by Rodowa et al. (2020) investigated PFAS in PVC liners and related materials, observing no quantifiable concentrations of routinely measured PFAS; however, it detected total fluorine (TF)

concentrations of up to 16,000  $\mu$ g F/m<sup>2</sup> in PVC liners. This suggests the potential presence of non-targeted PFAS or other fluorinated compounds, indicating the need to investigate total PFAS concentrations rather than relying solely on targeted analyses to fully assess contamination risks.

Given the widespread environmental persistence of PFAS, their potential health and ecological risks, and increasing regulatory scrutiny, there is a need to evaluate the extent of their possible use in geomembrane manufacturing, which will guide the necessity of updating current production processes and additive formulations to ensure safer practices. This study aims to advance knowledge in this area by investigating the presence of PFAS in HDPE geomembranes commonly employed in waste containment facilities and other engineering applications. To assess the presence and leachability of PFAS, extraction experiments were conducted using solutions with varying methanol concentrations. The study employed targeted analysis of six environmentally significant PFAS, alongside TF measurements, to assess the presence and concentrations of PFAS in geomembranes. TF analysis quantifies the total levels of fluorine present in a sample, including both known and unknown PFAS and other fluorinated chemicals, in both inorganic and organic forms (McDonough et al., 2019). Notably, the influence of inorganic fluorine is presumed to be negligible in geomembrane applications. By comparing the TF concentrations with the targeted PFAS analysis, the fractions of known and unknown fluorine compounds can be quantified and summed to derive "PFAS total" concentrations. This approach assumes conservatively that all detected fluorine originates from PFAS, which should be confirmed through targeted and, if necessary, non-targeted (NTA) analysis of PFAS.

#### 2. Materials and methods

#### 2.1.Geomembranes

The current study used three different commercially available HDPE geomembranes (GMBs) of varying thicknesses: GMB 1 (0.5 mm thick), GMB 2 (1.5 mm thick), and GMB 3 (2.0 mm thick), all manufactured between 2018 and 2021. GMB 1 was produced at a different manufacturing plant than GMB 2 and GMB 3. The geomembranes investigated are widely employed in the lining systems of waste containment facilities and other engineering applications. A summary of their main characteristics is presented in **Table 1**.

Properties	Standards	Units	Values		
-			GMB 1	GMB 2	GMB 3
Nominal thickness	ASTM F2251- 13	mm	$0.5 \pm 0.04$	1.5±0.04	2.0±0.04
Density	ASTM D792	g/cm <sup>3</sup>	0.9865	>0.940*	>0.940*
Standard Oxidation	ASTM D5885	g/cm <sup>3</sup>	212.62 <u>+</u> 5.4	206.23 <u>+</u> 4.22	197.3 <u>+</u> 3.69
Induction time (Std-					
OIT)					
High-Pressure	ASTM D5397	min	400	400	400
<b>Oxidation Induction</b>					
Time (HP-OIT)*					
Degree of	ASTM D3418	%	43.73 <u>+</u> 2.09	45.06 <u>+</u> 2.79	60.44 <u>+</u> 5.14
crystallinity					

Table 1 Main characteristics of the HDPE geomembranes investigated in the current study.

\* based on manufacturers datasheet

#### 2.2. Chemicals and Reagents

The analytes assayed for included two long chain PFAS, perfluorooctanesulfonic acid (PFOS), and perfluorooctanoic acid (PFOA), two short chain, perfluorobutanesulfonic acid (PFBS), and perfluorooctanoic acid (PFHxA), and three ultrashort chain PFAS, trifluoromethanesulfonic acid

(TFMS), pentafluoropropionic acid (PFPrA) and trifluoroacetic acid (TFA). These compounds were selected based on: (1) typical constituents detected in landfills, different aqueous environments, geotextiles, textiles and other consumer products, and drinking water (Gallen et al., 2017; Ateia et al., 2019; Bouazza, 2021; Neuwald et al., 2022; Xia et al., 2022; Mikhael et al., 2024a, b) (2) their diverse physicochemical properties and (3) available analytical techniques for their detection. PFAS standards used for calibration were purchased from Sigma-Aldrich (Australia) and Novachem (Australia). High-performance liquid chromatography (HPLC)- grade methanol ( $\geq$ 99.9%) was obtained from Sigma-Aldrich. All deionised (DI) water (>18 M $\Omega$ ) used was sourced from an in-house purification system operated by the Department of Civil Engineering at Monash University, Australia.

#### 2.3. Extraction experiments

The experiments were conducted in a PFAS-free environment. All equipment used was confirmed to be free of PFAS contamination. Before extraction, the geomembrane specimens were rinsed twice with DI water to remove any surface impurities. Specimens measuring 15 mm × 20 mm were immersed in polypropylene tubes containing 20 mL solutions. The coupon size was kept consistent across all samples to ensure comparability and to account for potential variations in extraction efficiency, particularly for thicker materials. The masses of the specimens were 15 mg, 42 mg, and 56 mg for GMB 1, GMB 2, and GMB 3, respectively. Solutions consisted of either 90% deionised (DI) water and 10% methanol or 100% methanol, with five replicates for each thickness and solution volume. This study utilised methanol as the extraction solvent, as it has been routinely employed for extracting PFAS from various matrices, including polymeric materials (Lorenzo et al., 2015; Rodowa et al., 2023; Michael et al., 2024a). The methods employed in these studies, which utilise sequential

solvent extraction cycles with methanol, have been demonstrated to minimise matrix effects and yield reproducible recoveries of PFAS. Furthermore, the use of methanol aligns with the USEPA method for "Quantitative Extraction and Analysis of PFAS from Plastic Container Walls" (2024). Methanol is an effective solvent for PFAS extraction due to its ability to interact with the non-polar carbon-fluorine (C-F) alkyl chains inherent to all PFAS (Lohmann et al., 2022). Methanol exhibits a greater affinity for the non-polar components of PFAS than water, promoting enhanced dissolution of these compounds. Additionally, methanol exhibits superior wetting properties compared to water, enabling it to spread more efficiently across surfaces and penetrate materials more effectively (Lohmann et al., 2022). In this study, 100% methanol was employed to determine the maximum potential concentrations of PFAS. In contrast, the 10% methanol/90% DI water mixture was utilised to create a less aggressive extraction environment. This dual approach aligns with the study's two primary aims: first, to assess the total amount of PFAS present in the geomembrane, and second, to evaluate the ease with which PFAS leach from the geomembrane.

The polypropylene tubes were shaken on an orbital shaker (NB-101M, N-Biotek) at 150 rpm and an ambient temperature of  $23 \pm 2^{\circ}$ C for 24 hours. After centrifugation, 1 mL of the supernatant was transferred to a 2 mL sample vial for liquid chromatography-mass spectrometry (LC-MS) analysis. Subsequently, the previous blank solution was replaced with a new one, and the tubes were shaken for an additional 24 hours. Following this, 1 mL of each supernatant was collected into a 2 mL vial for LC-MS analysis. This two-sampling method ensured thorough extraction of compounds from the geomembrane. The PFAS concentration was determined by summing the values obtained from the two extractions.

#### 2.4. Total Fluorine analysis

Total fluorine quantification was conducted in an accredited Australian National Association of Testing Authorities, NATA (ISO/IEC 17025) commercial laboratory. Samples were prepared by placing them in ceramic boats and subjecting them to pyrohydrolysis at 900–1000°C in a humid, oxygen-rich environment, oxidising the samples and breaking carbon-fluorine bonds. The resulting vapours, including HF, were passed through an absorption solution using Argon, where HF dissociated into H+ and F- ions. This solution underwent fluoride analysis using ion chromatography to quantify fluoride content. The method, LTM-INO-4370, a modification of the in-house method LTM-INO-4150 (Part A) and accredited by NATA (compliant with ASTM D7359-08), ensured precise measurement of fluoride levels in geomembranes.

#### 2.5. Quantitative analyses

PFAS concentrations in liquid samples were analysed using an ultra-high-definition liquid chromatography-quadrupole time-of-flight mass spectrometry instrument (LC-Q-TOF-MS). A standard calibration curve comprising five points was employed to quantitatively determine PFAS concentrations in the liquid phase. The method detection limit (MDL) for the analytes was established using a signal-to-noise ratio of 3:1, while the limit of quantification (LOQ) was determined based on a signal-to-noise ratio of 10:1. The LOQ for all compounds ranged from 0.02 to 0.1  $\mu$ g/L.

#### 2.6. Quality Assurance and Control

Before conducting the experiments, all tubes were rinsed with DI water and HPLC-grade methanol to prevent potential losses or contamination by PFAS. Fluorinated materials were excluded from the experiments to reduce the risk of contamination further. Instrumental

blanks containing DI water were used to assess the cleanliness of the LC-MS instrument. Method blanks, consisting of methanol and methanol/water solutions, were utilised to identify potential contamination and interference from sample manipulations, laboratory equipment, and the laboratory environment. Control tubes were prepared without adding a geomembrane to evaluate the presence of PFAS in the tubes. The laboratory blank results indicated no PFAS contamination, except for the tubes containing 90% DI water, which showed detectable concentrations of TFA in the water. As a result, TFA was excluded from the analysis of these samples.

#### 2.7.Fluorine equivalency determination

Fluorine mass balance analysis was performed by comparing target PFAS and TF concentrations. For this comparison, concentrations of target PFAS from the original extraction were converted to fluorine equivalency concentrations using the following equation:

$$C_F = C_{PFAS} \left( \frac{n_F A W_F}{M W_{PFAS}} \right)$$

Where  $C_F$  is the calculated fluorine concentration (µg F/g),  $C_{PFAS}$  is the concentration (µg/g) of each PFAS,  $n_F$  represents the number of fluorine atoms on each PFAS,  $AW_F$  denotes the atomic weight of fluorine (18.998 g/mol), and  $MW_{PFAS}$  is the molecular weight of each PFAS compound (g/mol).

#### 3. Results and Discussion

#### 3.1.Extraction Test

As shown in **Figure 1**, PFPrA was observed in all geomembrane specimens investigated. No other PFAS assayed in this study was detected in any specimens. For the 10% methanol solutions, the total concentrations of PFPrA ranged from below the LOQ to 0.09  $\mu$ g/g. In

contrast, PFPrA concentrations in the 100% methanol extractions ranged from 0.02 to 0.44  $\mu$ g/g. This difference was attributed to the higher methanol concentration, which enhanced the solvent's ability to interact with the non-polar components of PFPrA, facilitating better dissolution of the compound. Additionally, methanol's superior wetting properties likely facilitated more efficient spreading across the geomembrane surface and enhanced penetration, thereby improving the overall extraction process (Lohmann et al., 2022).

**Figure 1** shows that PFPrA concentrations in GMB 2 and GMB 3, manufactured at the same plant, were comparable. In contrast, GMB1, produced at a different facility, exhibited higher concentrations of approximately one order of magnitude. Specific details regarding the raw materials and processing conditions used for these geomembranes were not made available. However, the observed variation in leachable concentrations of PFPrA, particularly the higher concentrations in GMB 1 compared to GMB 2 and GMB 3, may be attributed to differences in the PPA formulations or PFAS-containing additives used by different manufacturing plants, as well as variability across batches produced at the same facility. For example, variations in the type or concentration of PFAS-based PPAs used during production could significantly influence the final PFPrA content in the geomembranes. Additionally, variations in production processes, such as the manufacturing temperature and extrusion speed, may affect the interaction between the geomembrane and PFPrA additives, further contributing to the observed discrepancies.



**Figure 1:** PFPrA concentration in each geomembrane sample. Error bars denote  $\pm$  one standard deviation for each geomembrane sample.

The detected concentrations of the ultrashort chain PFAS, PFPrA, may be attributed to the recent industrial shift toward using unregulated, shorter-chain fluorinated compounds in manufacturing (Crone et al., 2019). However, limited information is available regarding the use of these substances, particularly ultrashort-chain PFAS (those with 1–3 fully fluorinated carbon atoms). Ultrashort-chain PFAS are ubiquitous environmental contaminants, and their sources are poorly understood. These substances are often overlooked in analytical measurements, and their toxicological and ecotoxicological characteristics have been sparsely investigated (Brunn et al., 2023). Recent studies suggest that the significance of these substances has likely been severely underestimated. For example, surveys of Canadian rivers and rainwater have indicated that 40% of PFAS contamination can be attributed to ultrashort compounds (Yeung et al., 2017). Additionally, Neuwald et al. (2022) identified various ultrashort chain PFAS, including PFPrA

anions, in German drinking water supplies at concentrations ranging from 1 to 10 ng/L in nearly all samples. Furthermore, ultrashort-chain PFAA, such as TFA and PFPrA, have been detected in leachate from newer landfills at concentrations up to  $8.07 \times 10^4$  ng/L and were found to dominate over longer-chain PFAA (Wang et al., 2020). PFPrA has also been detected in clothing articles, suggesting its incorporation in the manufacturing of consumer products, likely due to the use of fluorinated compounds during production processes (Xia et al., 2022).

#### 3.2. Total Fluorine analyses

The average fluorine equivalency concentrations for the ultra-short-chain PFAS, PFPrA, were below the limit of quantification (LOQ) of 5 mg/kg for TF analysis in all geomembranes tested (see **Table 2**). Consequently, TF measurements were also below the reporting limit for all samples. TF analysis is less sensitive than LC-Q-TOF-MS for detecting specific PFAS and exhibits a higher LOQ (HEPA, 2020). This limitation likely led to excessive data censoring below the LOQ, highlighting the need for improved detection methods. Nonetheless, the non-detectable TF concentrations in the geomembranes of this study suggest that vast quantities of other PFAS were unlikely to be present in the samples.

Since TF concentrations below the LOQ do not provide a complete assessment of potential PFAS presence (as they may fail to capture low concentrations of fluorinated compounds), a more comprehensive analysis, including broader PFAS screening, would be necessary to confirm the absence of other PFAS. However, based on the current data, if other PFAS are present, they are likely to occur at relatively low concentrations.

Sample	Average Fluorine Equivalency Concentration (mg/kg)		
	10% Methanol	100% Methanol	
GMB 1	0.05	0.25	
GMB 2	0.01	0.03	
GMB 3	< LOQ	0.01	

**Table 2**: Average Fluorine Equivalency Concentrations for PFPrA in Geomembrane Specimens

## 4. Implications and Study Limitations

As regulatory scrutiny of the geomembrane industry intensifies, manufacturers must seek alternatives to PFAS-based PPAs or other additives if they are currently in use. Transitioning to environmentally friendly PPAs and additives is crucial for improving the sustainability and regulatory compliance of geomembrane production. However, a critical concern arises if regulated PFAS chemicals are replaced with unregulated or lesser-known alternatives, such as ultrashort PFAS. These substitute compounds may pose similar environmental and health risks as their predecessors, undermining the intended benefits of regulation. The issue is further compounded by the limited scientific data on newer PFAS, as highlighted by Wang et al. (2017). Adopting a precautionary regulatory approach to prevent unintended harm is essential to ensure all PFAS, including emerging variants, are thoroughly assessed and managed responsibly.

Although the concentrations of PFAS detected in geomembranes in this study were relatively low on a per-gram basis, their total mass could be significant when considering the vast scale of geomembrane applications, such as landfill liners, mining operations, and water containment systems. Given the large surface areas typically covered by geomembranes in such applications,

even low concentrations of PFAS could contribute to substantial cumulative environmental release over time. This long-term cumulative exposure poses potential risks to ecosystems and human health, highlighting the need for proactive measures to limit PFAS presence in geomembrane manufacturing.

This study acknowledges various limitations. First, the sample size of geomembranes analysed was limited, restricting the generalisability of the findings. Second, the study focused on a limited set of target analytes, leaving gaps in understanding the full spectrum of PFAS that may be present in geomembranes. To overcome these limitations, future studies should adopt a systematic approach that examines a broader range of geomembrane types and PFAS analytes, incorporating advanced techniques such as the total oxidisable precursor assay (TOPA) analysis. TOPA enables the detection of precursor compounds that can transform into measurable perfluoroalkyl acids (PFAAs), thus offering a more comprehensive assessment of PFAS in geomembranes. Additionally, the high limit of quantification (LOQ) for total fluorine (TF) constrained the ability to accurately determine total PFAS concentrations in geomembrane samples. Addressing these limitations in future research studies is essential for elucidating the extent of PFAS presence in geomembranes and drawing more broadly applicable conclusions.

Moreover, this study assessed the leachability of PFAS using water-methanol-based extraction methods; however, these methods do not replicate actual environmental conditions (e.g., pH, temperature, salinity, UV exposure, etc.). The processes controlling PFAS release require further investigation.

## 5. Conclusions

This study investigated the presence of PFAS in high-density polyethylene (HDPE) geomembranes, which are commonly used in waste containment facilities and hydraulic infrastructure. Based on the findings, the following conclusions were reached.

- PFPrA was detected in all examined geomembranes at concentrations ranging from below the limit of quantification (LOQ) to 0.44 μg/g.
- The concentration of PFPrA in the 100% methanol extractions (0.02 to 0.44  $\mu$ g/g) was notably higher than in the 10% methanol solutions (<LOQ to 0.09  $\mu$ g/g), suggesting that higher methanol concentrations improve extraction efficiency.
- PFPrA concentrations in GMB 2 and GMB 3, manufactured at the same facility, were comparable, while GMB 1, produced at a different plant, exhibited concentrations approximately one order of magnitude higher. This variation was attributed to differences in PPA formulations or PFAS-containing additives between plants, as well as variations in the production process.
- TF measurements were consistently below the LOQ for all samples, suggesting that significant quantities of other PFAS were unlikely to be present. The high detection limit of TF analysis likely contributed to excessive data censoring.
- Future research should investigate a broader range of geomembrane types and PFAS to enhance understanding of the occurrence and risks associated with PFAS in geomembranes.

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The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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