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Swimming with PFAS in public and private pools

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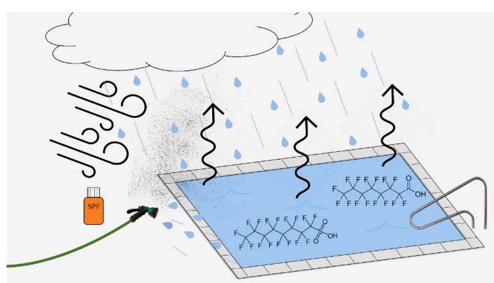
HIGHLIGHTS

- PFBA, PFHxA, PFHpA, PFOA, PFNA and PFBS were detected in every pool sample.
- Total ∑PFAS were similar (no statistical significance) across all samples regardless of pool type.
- PFHxA accounted for 49% of all quantitated PFAS in this study.
- The highest quantified ∑PFAS was 633 ppt in a city pool in Melbourne, Fl.
- Most PFOA and PFOS concentrations were above the new US EPA drinking water HAL.

GRAPHICAL ABSTRACT



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ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) are a class of anthropogenic chemicals used to provide water and stain resistance in many consumer products. Their widespread use, nearly ubiquitous presence across multiple environments, and growing list of adverse health effects has raised concerns among communities. PFAS have been frequently detected and quantified globally in wastewater, groundwater, surface and drinking water; however, the presence of PFAS in swimming pool water – a unique matrix in which constituents may concentrate through evaporation and which also may present a high risk of direct human exposure – has not been reported. Here, ultra-high performance liquid chromatography - tandem mass spectrometry (UHPLC-MS/MS) was used to monitor 92 PFAS in 54 water samples collected from city, apartment, hotel, and personal swimming pools in six Florida cities. In total, 14 PFAS were detected with six perfluoroalkyl acids – perfluorobutanoic acid (PFBA), perfluorohexanoic acid (PFHxA), perfluoroheptanoic acid (PFHpA) and perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA), and perfluorobutane sulfonate (PFBS) – detected in every sample. PFHxA accounted for 49% of all PFAS quantified in this study. PFAS profiles were compared between sites as a function of pool type, rate of use, and geographic location. Total ΣPFAS concentrations were similar across pool types, with both the highest (633 ng/L) and lowest (1.9 ng/L) measurements found in public city pools. Between sites, higher PFAS levels were observed in city pools in Miami, Melbourne and Tampa compared to Naples, Orlando and

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Gainesville. Our findings highlight the potential exposure of PFAS in an underexplored and yet important exposure pathway in communities.

1. Introduction

Per- and polyfluoroalkyl substances (PFAS) are a class of anthropogenic organic chemicals with fluorinated carbon chains of different lengths and functional groups (Newman, 2009). They have been used for decades in commercial products due to their stability and water and grease repellent properties (Zhang et al., 2022). PFAS exposure, particularly through contact or ingestion of contaminated water, has been linked to cancers, endocrine diseases, and a myriad of other adverse health effects, leading to concern over their persistence and ubiquity in the environment (Camdzic et al., 2022). Extensive research has been conducted to characterize the profile and potential sources of PFAS in a variety of water matrices (e.g., surface water, groundwater, wastewater, and drinking water) to reduce exposure risk and mitigate their adverse impacts (Camdzic et al., 2022; Oh et al., 2022; Pétré et al., 2022). Swimming pools are a less explored water matrix with the potential for high PFAS contamination depending on the source of potable water or groundwater, and the use of disinfectants and conditioners. Unlike northern states, in warmer climates, such as Florida, pools are not typically winterized (i.e., draining all water from the pool and associated systems during cold months, when pools are not in use to protect pool structures from expanding frozen water) and thus water remains year-round. Due to loss via evaporation, more water is added to warm-climate pools over the course of several months and years, resulting in a gradual concentration of recalcitrant constituents (e.g., salts) derived from source water or contributions during use in the water over time. Previous studies have detected several trihalomethanes, haloacetic acids, and endocrine disrupting chemicals, such as chloroform, trichloroacetic acid, and bisphenol, in pool water; however, this is the first comprehensive study to measure PFAS in water of different pool types (Sdougkou et al., 2021; Simard et al., 2013; Zhou et al., 2020).

In 2016, the US Environmental Protection Agency (EPA) released a drinking water guidance with health advisory levels (HAL) for the two most well studied PFAS – perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) – of 70 parts-per-trillion (ng/L) (US EPA, 2016), and more recently in June of 2022, the US EPA released a prepublication federal register notice on lifetime drinking water health advisories for four PFAS – PFOA and PFOS limits were reduced to 4 parts-per-quadrillion (pg/L) and 20 pg/L, respectively, and new HALs were added for GenX (10 ng/L) and PFBS (2 μg/L) (US EPA, 2022). These and other PFAS have been measured routinely in tap and groundwater (Domingo and Nadal, 2019) as well as in personal care products commonly used during outdoor activities, including pools (Brusseau et al., 2020; Thépaut et al., 2021). Here, water from 54 public and private pools, in six cities across Florida, underwent PFAS analysis using ultra-high performance liquid chromatography-tandem mass spectrometry (UHPLC-MS/MS). Public pool samples were collected from city-operated public pools accessible to the community as well as hotel and apartment complex-accessible pools, while private pools samples were collected from of personal home pools. PFAS concentrations in different pools were compared as a function of region and pool type (i.e., private, hotel, apartment complex, and public city pools; or indoor vs. outdoor pools) to identify characteristics that could be contributing to high PFAS contamination. This study also explored the understudied exposure route of PFAS via incidental ingestion of pool water, critical to understand health risks and to mitigate the impacts of overall PFAS burden.

2. Materials and methods

2.1. Chemicals and reagents

All solvents and reagents (methanol, acetonitrile, water, ammonium hydroxide, ammonium acetate and acetic acid) used in standard solutions and during sample extractions were Optima grade from Fisher Scientific (Waltham, MA, USA). A total of 92 PFAS (mixture of PFAC-24PAR and individual standards) were monitored, with 23 isotopically-labeled analogs (IS, mixture of MPFAC-24ES and individual standards) used as internal standards to quantify via isotope dilution. PFAS standards were purchased from Wellington Laboratories Inc. (Guelph, ON, Canada) or were donated from Synquest Laboratories Inc. (Alachua, FL, USA, abbreviated as Syn #) and Oakwood Products Inc. (Estill, SC, USA, abbreviated as Oak #)). All stock and internal standard solutions were prepared in Optima methanol. Additional information on PFAS monitored, abbreviations, and internal standard concentrations are included in the Supplementary Information (SI), Table S1.

2.2. Site location and sample collection

Discrete water samples from 54 swimming pools in six cities across Florida (Miami (n = 13), Gainesville (n = 15), Orlando (n = 9), Melbourne (n = 6), Naples (n = 6), and Tampa (n = 3)) were collected for PFAS analysis in the summer of 2021 (sites anonymized). Site information, including pool type, location, and whether the pool was indoor or outdoor are included in the SI Table S2. Samples were collected in 500 mL high density polyethylene (HDPE) bottles that were pre-rinsed at the collection site by filling and emptying each bottle with pool water three times before collection. All samples were kept on ice for transportation to the laboratory and stored in a freezer at −20 °C over the course of the sample collection period prior to sample extraction and analysis.

2.3. PFAS extraction

Swimming pool samples were randomized and thawed to room temperature prior to analysis. All sample bottles were gravimetrically weighed prior to and after solid phase extraction (SPE) to obtain the total mass of water extracted (g). The SPE method used Strata-X-AW cartridges (Polymeric Weak Anion Exchange, 500 mg, 100 μm, 6 cc) purchased from Phenomenex (Torrance, CA, USA) (Robey et al., 2020). All samples were acidified before extraction using glacial acetic acid to a pH of 3–4, then spiked with 25 μL of the IS mixture for quantification. All SPE cartridges were conditioned using 4 mL of 0.3% methanolic ammonium hydroxide, 3 mL of methanol and 4 mL of an ammonium acetate/acetic acid aqueous buffer solution (pH 4). Samples were loaded through the cartridges at a flow rate of 1–2 drops per second and washed using 4 mL of ammonium acetate/acetic acid buffer solution. All samples were spiked with the internal standard mixture prior to sample loading to correct for losses during sample preparation and extraction. Loaded cartridges were dried under vacuum for 10 min, then eluted into 15 mL centrifuge tubes using 2 mL of methanol and 6 mL of 0.3% methanolic ammonium hydroxide into 15 mL falcon tubes. Eluted samples were evaporated down to approximately 1 mL for subsequent mass spectrometric analysis.

2.4. Ultra-high performance liquid chromatography – tandem mass spectrometry

PFAS detection and quantitation was achieved using a Thermo

Scientific Vanquish UHPLC coupled to a TSQ Quantis triple quadrupole mass spectrometer. A Gemini C18 column (100 × 2 mm; 3 μm particle size) purchased from Phenomenex (Torrance, CA, USA) was used for chromatographic separation. Mobile phases of [A] water and [B] methanol, both with 5 mM ammonium acetate, were used with a gradient elution of 0–3 min at 10% B, 3–4.5 min changing from 10 to 35% B, 4.5–12.5 min changing from 35 to 95% B, 12.5–12.51 min changing from 95 to 99% B, and 12.51–19 min at 99% and then set back to the initial conditions. Flow rate and injection volume were set to 0.5 mL/min and 10 μL, respectively. Mass spectra were obtained in negative polarity in selected reaction monitoring mode (SRM). Sheath and auxiliary gas were set to 60 and 5 arb, respectively, and ion spray voltage was set to −3000 V. Ion transfer tube temperature was set to 325 °C and the vaporizer temperature was set to 350 °C, respectively. Table S3 in the SI lists all instrument parameters used in this study as well as the PFAS SRM transitions.

2.5. Quality assurance and quality control (QA/QC)

The performance of the extraction and analytical methods described here have been validated previously (da Silva et al., 2022; Robey et al., 2020) for the expanded suite of PFAS, and method performance is reported in the SI for PFAS quantified in at least one swimming pool sample. Quality control (QC) samples were used to assess the performance of the analysis and consisted of Optima-grade water spiked with a known concentration of PFAS (at 1.7 ng/L). The experimentally-derived concentrations were then compared to the expected concentrations to check accuracy. All pool, blank, and QC samples were extracted and analyzed randomly via UHPLC-MS/MS. Relative standard deviation (RSD) for the QC samples were calculated to determine precision. All data presented in this study was within the acceptable precision (relative error $<20\%$), as shown in Table S4. All detection and quantitation limits were set to a signal to noise ratio greater than 3 and 10, respectively. Methanol solvent blanks were included in the sequence to assess background levels and potential carryover. Xcalibur v.4.1 software (Thermo Fisher Scientific) was used for data acquisition and manual peak integration. PFAS were detected and quantified using the most intense SRM transition and their identities were confirmed using their second transition (when applicable). For PFAS that did not have a corresponding internal standard, alternative isotopically-labeled standards with similar retention time or structural similarities were chosen for quantitation.

3. Results and discussion

Across all 54 pool samples, 14 PFAS were identified in at least one sample. However, the number of PFAS detected at each site ranged from 3 to 12 different PFAS. There was no evident difference in the number of PFAS detected between the different types of pools or between region, suggesting PFAS concentration in swimming pools might be driven by a common source. Total PFAS concentrations (Σ_{14}PFAS) in swimming pools ranged from 1.0 ng/L to 633 ng/L (mean: 41 ± 90 ng/L). Detected PFAS included eight perfluorinated carboxylic acids (PFCAs) (C4–C11), four PFSAs (C3–C4, C6, C8), one fluorotelomer (6:2 FTCA) and one hydrogen-substituted PFAS (7H-dodecafluoroheptanoic acid). Two PFCAs, perfluorobutanoic acid (PFBA) and perfluorohexanoic acid (PFHxA) were quantified in 100% of samples at mean concentrations of 3.5 ± 2.8 ng/L and 20 ± 71 ng/L, respectively. PFBS and PFOA were also prevalent in swimming pool water, with a total of 94% frequency of detection. The maximum single measurement was 508 ng/L of PFHxA, which was recorded in a sample from a public city pool in Melbourne – the same pool also had the highest Σ_{14}PFAS of 633 ng/L. PFHxA had the highest concentration of PFAS in 83% of the samples ($n = 46$), followed by PFBA, which had the highest concentration in 13% of the samples ($n = 7$) and PFPeA, in the remaining sample ($n = 1$). PFHxA accounted for 34% of Σ_{14}PFAS concentration, on average across all samples. PFHxA concentrations correlated most strongly with Σ_{14}PFAS, with $R^2 = 0.97$ among all 54 samples and $R^2 = 0.87$ with the exclusion of one extreme value (the high concentration sample from the city pool in Melbourne). A scatterplot of PFHxA concentrations versus Σ_{14} PFAS is included in the SI Figure S1. The concentrations of each PFAS for all samples is included in the SI Table S2.

Σ_{14}PFAS concentrations between pool types (i.e., apartment, city, hotel, and personal swimming pools) did not vary significantly from each other ($p > 0.3$). The entire sample set from "public" pools, which included apartment, city, and hotel pools, was not significantly different from personal swimming pools ($p = 0.9$), as shown in Fig. 1. The single indoor pool included in this study (a city pool in Melbourne) had Σ_{14}PFAS lower than most sites (4.9 ng/L and in the 5th percentile among all samples). Because indoor pools do not experience environmental impacts such as rainfall, evaporation as significantly as outdoor pools, and indoor pool users are less likely to apply sunscreen, which may contribute PFAS to the water, this finding is not surprising; however, it only represents a single sample and may simply be a function of sample variability. Samples from the city of Gainesville had the lowest mean Σ_{14}PFAS, 14.2 ng/L, while Melbourne had the highest mean Σ_{14}PFAS, 127 ng/L, driven primarily by the highest measurement of any sample, 635 ng/L; however, the median Σ_{14}PFAS in Melbourne (32.8 ng/L) was similar to the median across all other Florida sample sites of 26.4 ng/L. A box and whisker plot with Σ_{14}PFAS for each city is included in the SI Fig. 2.

Concentrations of the five PFAS quantified in this study for which the US EPA has released tap water regional screening levels (RSL) – PFOA, PFOS, PFHxS, PFNA, and PFBS – were consistently lower than their respective RSLs (60 ng/L, 40 ng/L, 390 ng/L, 59 ng/L, and 6000 ng/L, respectively). PFOS was detected above LOD in all but seven samples (above LOQ in 19 samples and below LOQ but above LOD in 28) and PFOA was detected above LOD in all samples (above LOQ in 51). PFOA accounted for 7.14% of all measured PFAS while PFOS accounted for 2.49%. The mean concentrations of PFOS and PFOA across all samples were 1.0 and 2.9 ng/L, respectively, The highest measured concentration of PFOS was observed in a Miami city pool (17.6 ng/L), while the highest PFOA concentration was also found in another Miami city pool (11.8 ng/L).

Table 1 shows the health advisory levels for PFOS and PFOA set by the US EPA, as well as individual states which have promulgated their own risk-based thresholds.[9] Florida, where this study was conducted, has released provisional groundwater cleanup target levels which correspond with previous EPA drinking water guidance levels (70 ng/L for PFOA and PFOS) (Stuchal and Roberts, 2019). All samples surpassed the US EPA pre-published health advisory limits for either PFOS or PFOA (PFOA: 4 pg/L and PFOS: 20 pg/L), and since the detection limit of the method (and essentially all published methods) is higher than the advisory limit, it cannot be stated definitively whether any samples were below the advisory limit (US EPA, 2022). High concentrations of PFOS and PFOA, among the other PFAS detected, in these city pools can serve as a possible route of exposure for swimmers. With the new EPA health advisory (PFOS and PFOA consumption of 0.02 ng/L and 0.004 ng/L) and the average accidental ingestion rates of swimming pool water determine by Dufour et al. (23.9 mL per hour for children and 12.4 mL per hour for adults), frequent swimmers in these PFAS-laden pools may be exposed to health-adverse levels of PFOS and PFOA in both the short and long term (Dufour et al., 2017; Zhou et al., 2020).

Past research has measured fluorinated compounds in personal care products, such as sunscreen and makeup, including PFOA and PFHxA (Fujii et al., 2013; Whitehead et al., 2021), which may explain the high levels of PFHxA found in some samples. PFHxA is also a common breakdown product of other PFAS used in consumer products, which may also contribute to its prevalence in pool water (Buck et al., 2011). PFAS have been measured in rainwater, groundwater and domestic tap water, as well as dust from surrounding areas, which may also be a source of PFAS in swimming pools (Ahmadireskety et al., 2021; Arp and Goss, 2009; Hall et al., 2020; Li et al., 2022; Martinez et al., 2022;

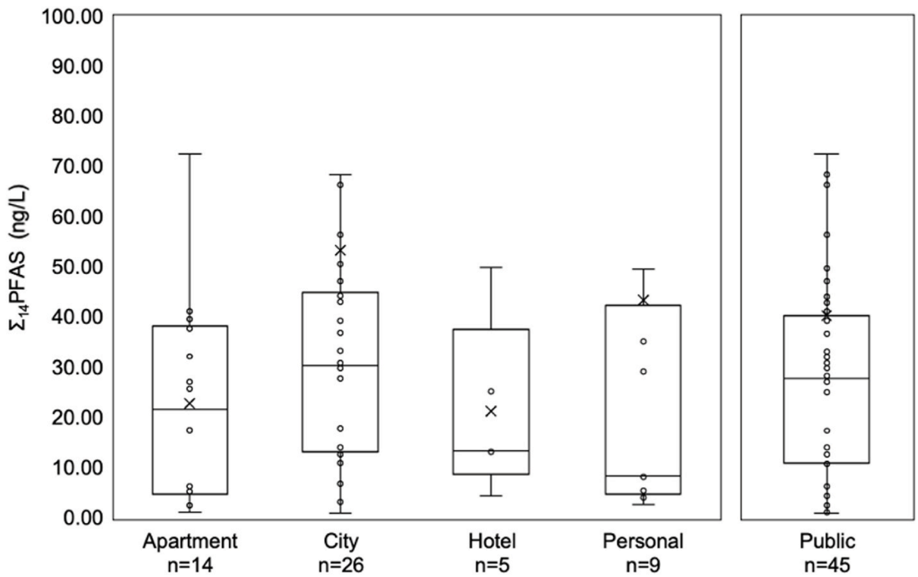

Fig. 1. Box and whisker plots of total PFAS concentration in 54 water samples collected from swimming pools in Florida, USA. Plots include 10th, 25th, 50th, 75th and 90th percentiles, X represents the mean value. The plot for "public" pools includes all sites except for personal swimming pools (i.e., includes apartment, city, and hotel pools). Summary statistics include one extreme data point among the city pool samples (Σ_{14}PFAS = 635 ng/L) and one among personal pools (Σ_{14}PFAS = 249 ng/L), both not shown in the figure.

Table 1
Health advisory limits (ng/L) for PFOA and PFOS set by the US EPA and several states for different water matrices (DW = drinking water, GW = groundwater, SW = surface water), and the number of sites with levels higher than the respective limit.

Agency or State	Matrix	Year Issued	PFOA	PFOS	Samples with PFOA above the risk-based threshold (/54)	Samples with PFOS above the risk-based threshold (/54)
US EPA	DW	2022	0.004[a]	0.02[a]	54	47
US EPA	DW (tap)	2016	60	40	0	0
CA	DW	2021	40	10	0	2
CO	GW, SW	2020	70[a]	70[a]	0	0
CT	DW	2020	70[a]	70[a]	0	0
FL	GW	2020	70 [a]	70 [a]	0	0
IL	GW	2021	21[a]	21[a]	0	1
MA	DW	2020	20[a]	20[a]	0	1
MI	DW	2020	8	16	0	3
MN	DW	2019	35	15	0	0
NH	DW, GW	2020	12	15	0	1
NJ	DW	2020	14	13	0	1
NY	DW, GW, SW	2020	10	10	1	2
OH	DW	2019	70[a]	70[a]	0	0
RI	DW, GW, SW	2020	20[a]	20[a]	0	1
VT	DW	2020	20[a]	20[a]	0	1
WA	DW	2016	10	15	0	2

[a] Limit for individual and total concentrations of PFOS and PFOA.

Nyholm et al., 2013). Compounds, such as PFOS and PFOA have been measured in dust and street sweepings, which can find their way into pools through wind or storm events. All of these environmental and anthropogenic influences are possible explanations for PFAS contamination in swimming pool water, and the evaporation of water in the swimming pool can lead to increased concentrations of PFAS over time, as the volume of water in the pool decreases and PFAS are left behind. While debris such as plant matter and textiles are filtered out of pool water as part of pool operation, PFAS are not actively removed and may continually reside and accumulate in the water.

Repeated exposure to these compounds can lead to possible adverse health effects, such as cancer and endocrine disorders/diseases (Li et al., 2022; Luz et al., 2019). With recent changes to the health advisory limits of PFOA and PFOS by the EPA, and with likely future limits set forth for other ubiquitous PFAS, it is necessary to consider the risk of PFAS exposure through accidental ingestion in swimming pools for frequent users, especially children, who may have an elevated PFAS burden from this exposure route. Addressing PFAS contamination in tap and groundwater (which are common sources for swimming pool water), implementing strategies to remove PFAS from pools, and highlighting the use of PFAS in consumer products, will be necessary in order to reduce the overall burden of PFAS in pools.

Author contributions statement

Brian Martinez: Conceptualization; Data curation; Validation; Roles/Writing – original draft; Writing – review & editing, Nicole M. Robey: Data curation; Investigation; Validation; Roles/Writing – original draft; Writing – review & editing, Bianca F. Da Silva: Data curation; Methodology; Validation; Writing – review & editing, Heather Ditz: Formal analysis; Investigation; Writing – review & editing, William J. Sobczak: Formal analysis; Investigation; Writing – review & editing, Katherine Y. Deliz Quiñones: Funding acquisition; Writing – review & editing, John A. Bowden: Conceptualization; Data curation; Funding acquisition; Supervision; Validation; Roles/Writing – original draft; Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chemosphere.2022.136765.

References

Ahmadireskety, A., Da Silva, B.F., Robey, N.M., Douglas, T.E., Aufmuth, J., Solo-Gabriele, H.M., Yost, R.A., Townsend, T.G., Bowden, J.A., 2021. Per- and polyfluoroalkyl substances (PFAS) in street sweepings. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.1c03766.

Arp, H.P., Goss, K.-U., 2009. Gas/particle partitioning behavior of perfluorocarboxylic acids with Terrestrial aerosols. Environ. Sci. Technol. 43, 8542–8547.

Brusseau, M.L., Anderson, R.H., Guo, B., 2020. PFAS concentrations in soils: background levels versus contaminated sites. Sci. Total Environ. 740, 140017 https://doi.org/10.1016/j.scitotenv.2020.140017.

Buck, R.C., Franklin, J., Berger, U., Conder, J.M., Cousins, I.T., de Voogt, P., Jensen, A.A., Kannan, K., Mabury, S.A., van Leeuwen, S.P., 2011. Perfluoroalkyl and polyfluoroalkyl substances in the environment: terminology, classification, and origins. Integrated Environ. Assess. Manag. 7, 513–541. https://doi.org/10.1002/ieam.258.

Camdzic, M., Aga, D.S., Atilla-Gokcumen, G.E., 2022. Cellular interactions and fatty acid transporter CD36-mediated uptake of per- and polyfluorinated alkyl substances (PFAS). Chem. Res. Toxicol. 35, 694–702.

da Silva, B.F., Aristizabal-Henao, J.J., Aufmuth, J., Awkerman, J., Bowden, J.A., 2022. Survey of per- and polyfluoroalkyl substances (PFAS) in surface water collected in Pensacola, FL. Heliyon 8, e10239. https://doi.org/10.1016/j.heliyon.2022.e10239.

Domingo, J.L., Nadal, M.H., 2019. Exposure to per- and polyfluoroalkyl substances (PFAS) through drinking water: a review of the recent scientific literature. Environ. Res. 177, 108648.

Dufour, A.P., Behymer, T.D., Cantú, R., Magnuson, M., Wymer, L.J., 2017. Ingestion of swimming pool water by recreational swimmers. J. Water Health 15, 429–437.

Fujii, Y., Harada, K.H., Koizumi, A., 2013. Occurrence of perfluorinated carboxylic acids (PFCAs) in personal care products and compounding agents. Chemosphere 93, 538–544.

Hall, S.M., Patton, S., Petreas, M., Zhang, S., Phillips, A.L., Hoffman, K., Stapleton, H.M., 2020. Per- and polyfluoroalkyl substances in dust collected from residential homes and fire stations in North America. Environ. Sci. Technol. 54, 14558–14567.

Li, X., Fatowe, M., Cui, D., Quinete, N., 2022. Assessment of per- and polyfluoroalkyl substances in Biscayne Bay surface waters and tap waters from South Florida. Sci. Total Environ. 806, 150393.

Luz, A.L., Anderson, J.K., Goodrum, P., Durda, J., 2019. Perfluorohexanoic acid toxicity, Part I: development of a chronic human health toxicity value for use in risk assessment. Regul. Toxicol. Pharmacol. 103, 41–55.

Martinez, B., Silva, B.F., Aristizabal-Henao, J.J., Denslow, N.D., Osborne, T.Z., Morrison, E.S., Bianchi, T.S., Bowden, J.A., 2022. Increased levels of perfluorooctanesulfonic acid (PFOS) during Hurricane Dorian on the East Coast of Florida. Environ. Res. 208, 112635.

Newman, M.C., 2009. Fundamentals of Ecotoxicology.

Nyholm, J.R., Grabic, R., Arp, H.P.H., Moskeland, T., Andersson, P.L., 2013. Environmental occurrence of emerging and legacy brominated flame retardants near suspected sources in Norway. Sci. Total Environ. 443, 307–314. https://doi.org/10.1016/j.scitotenv.2012.10.081.

Oh, J., Shin, H.-M., Nishimura, T., Rahman, M.S., Takahashi, N., Tsuchiya, K.J., 2022. Perfluorooctanoate and perfluorooctane sulfonate in umbilical cord blood and child cognitive development: Hamamatsu birth cohort for mothers and children (HBC study. Environ. Int. 163, 107215.

Pétré, M.-A., Salk, K.R., Stapleton, H.M., Ferguson, P.L., Tait, G., Obenour, D.R., Knappe, D.R.U., Genereux, D.P., 2022. Per- and polyfluoroalkyl substances (PFAS) in river discharge: modeling loads upstream and downstream of a Pfas manufacturing plant in the Cape fear Watershed, North Carolina. Sci. Total Environ. 831, 154763.

Robey, N.M., da Silva, B.F., Annable, M.D., Townsend, T.G., Bowden, J.A., 2020. Concentrating per- and polyfluoroalkyl substances (PFAS) in municipal solid Waste landfill leachate using foam separation. Environ. Sci. Technol. 54, 12550–12559. https://doi.org/10.1021/acs.est.0c01266.

Sdougkou, A., Kapsalaki, K., Kozari, A., Pantelaki, I., Voutsa, D., 2021. Occurrence of disinfection by-products in swimming pools in the area of Thessaloniki, northern Greece. Assessment of multi-pathway exposure and risk. Molecules 26, 7639.

Simard, S., Tardif, R., Rodriguez, M.J., 2013. Variability of chlorination by-product occurrence in water of indoor and outdoor swimming pools. Water Res. 47, 1763–1772.

Stuchal, L., Roberts, S., 2019. PFAS - Provisional Cleanup Target Levels and Screening Levels.

Thépaut, E., Dirven, H.A.A.M., Haug, L.S., Lindeman, B., Poothong, S., Andreassen, M., Hjertholm, H., Husøy, T., 2021. Per- and polyfluoroalkyl substances in serum and associations with food consumption and use of personal care products in the Norwegian biomonitoring study from the EU project EuroMix. Environ. Res. 195, 110795.

US EPA, 2022. Drinking Water Health Advisories for Four Per- and Polyfluoroalkyl Substances (PFAS) PFOA, PFOS, GenX Chemicals, and PFBS.

US EPA, 2016. Drinking Water Health Advisories for PFOA and PFOS.

Whitehead, H.D., Venier, M., Wu, Y., Eastman, E., Urbanik, S., Diamond, M.L., Shalin, A., Schwartz-Narbonne, H., Bruton, T.A., Blum, A., Wang, Z., Green, M., Tighe, M., Wilkinson, J.T., McGuinness, S., Peaslee, G.F., 2021. Fluorinated compounds in North American Cosmetics. Environ. Sci. Technol. Lett. 8, 538–544.

Zhang, Z., Sarkar, D., Biswas, J.K., Datta, R., 2022. Biodegradation of per- and polyfluoroalkyl substances (PFAS. A review. Bioresour. Technol. 344, 126223.

Zhou, X., Peng, F., Luo, Z., Li, Y., Li, H., Yang, Z., 2020. Assessment of water contamination and health risk of endocrine disrupting chemicals in outdoor and indoor swimming pools. Sci. Total Environ. 704, 135277.