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Occurrence of forever chemicals in Chennai waters, India

G. V. Koulini¹ and Indumathi M. Nambi^{1*}

Abstract

Background Per- and polyfluoroalkyl substances (PFAS) are considered ‘contaminants of emerging concern’ due to their environmental persistence, bio-accumulative potential, and adverse effects on human health. They are widely employed in producing various goods used in daily life, such as non-stick cookware, cleaning agents, and many industrial applications in aerospace, automotive, construction, electronics, and military, all of which ultimately end up in different environmental matrices. India’s rapid economic growth necessitates a comprehensive understanding of its PFAS contamination levels and potential human and ecological exposure.

Results The present study reports the quantification of one long-chain and two short-chain perfluoroalkyl acids and three long-chain and two short-chain perfluorosulfonic acids and qualitative analysis using suspect screening in the waters of Chennai, Tamil Nadu, India. Samples were collected from surface and groundwater sources, including the Adyar river, Buckingham canal, Chembarambakkam lake, and the water treatment plant. The concentrations analyzed in all the samples ranged from 0.10 ng/L to 136.27 ng/L. Groundwater had some of the highest concentrations of PFAS. L-PFBS (up to 136.27 ng/L) and PFOA (up to 77.61 ng/L) are present in all the samples. The concentrations of all the target PFAS increased in the 5 to 103% range in the final treated water compared to the raw water of the water treatment plant. This treated water is distributed as a source of drinking water for the residents of Chennai. Additionally, the dominance of short-chain compounds (4–7 carbons) over long-chain compounds (> 7 carbons) was observed. Suspect screening revealed numerous precursors and other fluorinated compounds abundantly present in the samples.

Conclusions Our study revealed PFAS levels up to 136.27 ng/L in both surface and groundwater samples from Chennai. These findings raise concerns about potential risks to ecosystems and human well-being. The dominance of short-chain PFAS coupled with abundant precursors and unidentified fluorinated compounds indicates an ongoing shift toward alternatives. Conventional water treatment is ineffective in eliminating these chemicals from the water system; rather, increasing the PFAS concentrations from raw water to treated water necessitates advanced polishing steps. Industrial emissions, untreated domestic wastewater discharge, and open dump sites have been suspected as the significant sources of contamination, highlighting the need for further investigation to fully assess the extent of PFAS contamination in Chennai.

Highlights

- Groundwater and surface waters showed predominant presence of PFOA and L-PFBS.
- Concentrations of target PFAS increased from raw water to treated water in a conventional WTP.

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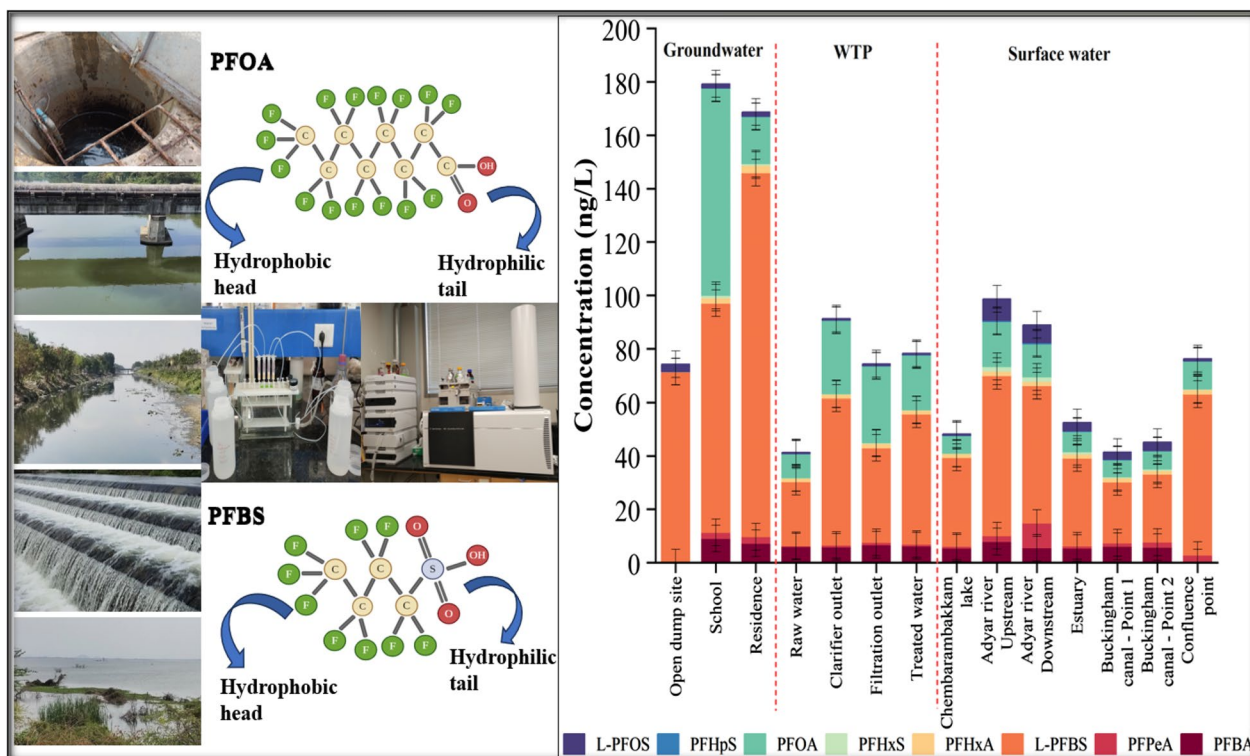


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- Numerous precursors and other fluorinated compounds are abundantly present in the collected samples.
- Open dump sites, untreated domestic wastewater discharge, and industrial emissions have been suspected as the contributing sources.

Keywords Chennai, Detection, Forever chemicals, Occurrence, PFAS, Suspect screening, Waters

Graphical Abstract



Background

Per- and polyfluoroalkyl substances (PFAS) are a vast family of more than 10,000 manufactured organic chemicals [1] known for their versatility in being used as surfactants and repellents. The hydrophobic/lipophobic alkane chain, where the hydrogen atoms are replaced entirely (per-) or partially (poly) by fluorine atoms and a hydrophilic functional group, gives them their unique nature. High electronegativity, $E^0 = 3.6$ V [2], and the small size of the fluorine atom make the C–F bond (bond dissociation energy – 105.4 kcal/mol the strongest covalent bond [3], hence, nicknamed ‘forever chemicals’. PFAS have numerous applications in everyday products such as non-stick cookware, upholstery, food packaging, water/oil/stain resistant coatings, and firefighting gear and agents such as AFFF [4, 5].

They also have enormous industrial applications in aviation, automobile, construction, electronics, and military [6]. These emerging contaminants are persistent in the environment and the human body, causing adverse effects such as liver damage, low infant birth weights, hormonal imbalance, fertility issues, immune system effects, and even cancer [7–9]. Due to their ubiquitous nature, PFAS have also been detected in various environmental matrices such as sediment, algae, and animals of Antarctica [10].

In recent years, the long-chain PFAS known as the legacy PFAS (PFOA, PFOS, etc., having >7 carbons) have been replaced by short-chain PFAS (GenX, PFBS, PFBA, etc., having 4–7 carbons) and ultra-short-chain PFAS (PFPrA, PFETs, PFPrS, etc., having 2–3 carbons) [11, 12]. The hydrophilic nature of the short/ultra-short-chain

Table 1 US EPA drinking water health advisory levels

Compound	Limit (ng/L)
Interim PFOA	0.004
Interim PFOS	0.02
Final GenX	10
Final PFBS	2000

Table 1 highlights the drinking water health advisory levels released by the US EPA in June 2022

alternatives has resulted in widespread occurrence due to higher solubility and mobility in the environment than legacy PFAS, which are comparatively less mobile and more bioaccumulative [13]. Studies are on the rise to understand the environmental impacts of these alternatives.

The Stockholm Convention's Conference of the Parties included PFOS, its salts, and PFOSF in Annex B (2009), and PFOA, its salts, and related chemicals in Annex A (2019). Refer to <https://www.pops.int/TheConvention/ThePOPs/AllPOPs/tabid/2509/Default.aspx>. Landfills/open dump sites, industrial emissions/effluent discharges, and direct application of AFFF and biosolids are some of the significant pathways of PFAS entering the environment [14–17]. Many countries and jurisdictions have started to regulate or restrict the use of PFAS in certain products, and there is ongoing research into these chemicals' health and environmental impacts. In June 2022, the US EPA released the drinking water health advisory levels for the four most commonly used chemicals, PFOA, PFOS, and their short-chain substitutes GenX and PFBS, respectively, as shown in Table 1 [18].

Knowledge gaps exist within the vast PFAS class. Also, limited numbers in the class are highly studied. PFAS contamination is a pressing global issue demanding immediate attention. Developing new monitoring and modeling approaches, filling knowledge gaps, and implementing stricter regulations are critical to mitigate their adverse health and environmental impacts [19].

India is a fast-developing country with rapid industrialization and economic development, resulting in increased usage of PFAS due to their extensive applications. Comprehensive information on the production, use, and waste management of PFAS in India is limited [20]. A study conducted by [21] showed the presence of these forever chemicals in Indian human hair across 14 cities, ranging from <0.02 ng/g to 3.78 ng/g. The aim of the present study was both quantitative and qualitative detection of these persistent chemicals in the waters of the metropolitan city of 'Chennai' in the Indian state of Tamil Nadu. This work is unique in terms of thorough sampling that includes ground and surface water sources contaminated by the leachate from an open dump site

and untreated domestic wastewater discharge, respectively. Additionally, samples were included from every stage of a significant water treatment plant where the raw water is sourced from a lake surrounded by industries. Various sampling sites were selected to capture different geographical locations and potential PFAS sources. This enables a comprehensive understanding of the presence of PFAS in a wide range of contamination from low to high in water bodies of Chennai. Also, this will help assess exposure to humans through water supply sources and quantify the ecological impact in Pallikaranai marshland, a Ramsar site near the open dump site (refer to Fig. 1A). The Chennai city waters are already known for the occurrence of a variety of pharmaceuticals [22, 23], heavy metals [24], and microplastics [25]. Therefore, scanning for fluorinated chemicals is necessary for this scenario. Quantification of eight target PFAS, i.e., two short-chain PFCAs (PFHxA and PFPeA) and PFSAs (L-PFBS and PFBA), one long-chain PFCA (PFOA), and three long-chain PFSAs (PFHpS, L-PFOS, and PFHxS), as well as suspect screening and risk assessment analysis, was carried out in the present study.

Methods

Study area

Chennai is the capital city of the southernmost state of India, Tamil Nadu. The city's water needs are fulfilled by various water sources, including reservoirs, desalination facilities (Nemelli and Minjur), groundwater, and rivers (Cauvery and Krishna). The city's four primary freshwater reservoirs are Poondi, Red Hills, Cholavaram, and Chembarambakkam. The city has four WTPs located at Kilpauk (270 MLD), Puzhal (300 MLD), Vadakuthu (180 MLD), and Chembarambakkam (530 MLD). The 530 MLD Chembarambakkam WTP is the second-largest plant in India. Adyar, Cooum, and Kosasthalaiyar are three rivers that flow through the city and drain into the Bay of Bengal. All three of these rivers are connected by the Buckingham canal.

Sampling

Three liters of each sample were collected using one and two-liter HDPE bottles pre-rinsed with methanol and deionized water. Fourteen water samples were collected from December 2022 to February 2023 and stored at 4 °C until extraction (within 24 h). Of the fourteen, three were groundwater samples collected through bore wells after pumping the water for 10 min. These included the Perungudi open dump site, a school, and a residence one km from the dump site. Seven were surface water samples collected at a depth of 0.5 m below the surface level. These included two locations along the Buckingham canal and CP of the Buckingham canal and Adyar



Fig. 1 Water sampling locations in Chennai, Tamil Nadu, India. **A** showing the three sampling points inside the Perungudi open dump site. **B** showing the five sampling points from Chembarambakkam lake and all stages of WTP (raw water, clarifier outlet, filtration outlet, and treated water). **C** showing the four sampling points along the Adyar river, estuary (Adyar river and Bay of Bengal confluence), and confluence point of Buckingham canal and Adyar river. **D** showing the two sampling points along the Buckingham canal

river, two locations (U/S and D/S of the CP) and an estuary (Adyar river and Bay of Bengal confluence) along the Adyar river, and the lake of Chembarambakkam. The remaining four were grab samples collected from all stages (raw water, clarifier outlet, filtration outlet, and treated water) of a WTP. The WTP is based on the conventional treatment of cascade aeration, clariflocculation, rapid sand filtration, and chlorine disinfection. The sampling points' locations are shown in Fig. 1, and latitude and longitude are available in Additional file 1: Table S1 of Additional material.

Chemicals and reagents

Ammonium acetate (ACS reagent $\geq 97\%$, CAS # 631-61-8) was sourced from Sigma_Aldrich, India, ammonium hydroxide (ACS grade 28–30%), and glacial acetic acid were sourced from Merck, and LC–MS grade methanol was purchased from Fisher Chemical, India. Whatman glass microfiber filters (GF/A) diameter 47 mm supplied by GE Healthcare Life Sciences. 0.22 μm size nylon syringe filters purchased from Rankem. Sample bottles (0.5, 1, and 2 L), centrifuge tubes, and pipette tips were purchased from Tarsons, and autosampler 2 mL vials were purchased from Agilent, all made of polypropylene. Elga water was used for all purposes unless otherwise

specified. Standards were prepared using methanol. Analytical standards of LC target compounds were purchased from Wellington Laboratories. The details of the analytical standards are given in Additional file 1: Table S2 of the Additional material.

Extraction method

Solid phase extraction of the collected water samples was carried out using Oasis WAX Cartridge 6 cc/500 mg 60 μm purchased from Waters India Private Limited. The cartridges were conditioned using 4 mL each of 0.5% ammonium hydroxide in methanol, methanol, and water, respectively. Then, one liter of the sample was loaded onto the cartridge drop by drop. The sides of the sample containers were rinsed with ultrapure water and passed through the cartridge. The cartridges were rinsed using 4 mL each of 25 mMol/L ammonium acetate in water acidified to pH 4 using glacial acetic acid and water. Then, the target PFAS were eluted using 4 mL each of methanol and 0.5% ammonium hydroxide in methanol. The eluted samples were dried using a gentle stream of nitrogen gas till 0.5 μL and made up to 1 mL using 100% LC–MS grade methanol. All the extract samples were filtered using 0.22 μm size nylon syringe filters and stored in autosampler vials at $-20\text{ }^\circ\text{C}$ before instrumental analysis.

Analytical method

The basic water quality parameters were analyzed following the APHA protocol. Heavy metals were quantified using Agilent make ICP-OES 5110. Quantification of target PFAS and suspect screening was performed on an Agilent make LC-QTOF-MS using ZORBAX RRHD Eclipse Plus 95 Å, 2.1×150 mm, 1.8 μm. 10 mMol/L ammonium acetate and 100% methanol were used as mobile phases A and B, respectively, with a 0.4 mL/min solvent flow rate. The analysis was carried out in positive and negative electron spray ionization modes for a run time of 31.5 min at collision energies of 0, 10, 20, and 40 eV. The gradient was maintained as follows: 25%B for 1.5 min, 25–90%B in 25 min, and 100% B for 5 min, followed by equilibration to initial conditions for 3 min. The injection volume was 10 μL. The other conditions were: column temperature 30 °C, gas temperature 300 °C, drying gas flow 12 L/min, nebulizer 25 psig, sheath gas temperature, and flow 350 °C and 11 L/min, respectively. The scan range and speed are 50–1200 m/z and 4 spectra/s, respectively, with 110 V fragmentor and 3000 neg Vcap. The 19-internal standard dosed ten-point calibration curve (0.5–250 ng/mL) was used for quantification. 10μL of an internal mix standard consisting of 1 μg/mL of a mixture of PFHxS, L-PFOS, L-PFBS, PFOA, and PFBA was added to 200 μL of each sample before injecting the sample into LC-QTOF-MS.

Quality assurance and quality control

The trace-level analytical process was subjected to stringent quality control and assurance. All known contamination sources were eliminated to reduce background contamination throughout the procedure. The use of glassware was minimized, and polypropylene was only used. The concentrations were not corrected for the recoveries. Quantification (LOQ) limits range from 0.025 to 1 ng/mL for the whole method.

Results

The basic water quality parameters are listed in Additional file 1: Table S3 and the presence of heavy metals in Additional file 1: Table S3.1 of the supplementary material. All the collected samples were quantified for eight targets, i.e., PFHxA, PFPeA, L-PFBS, PFBA, PFOA, PFHpS, L-PFOS, and PFHxS, and suspect screening analysis was done at the University of California, Davis, United States of America. The target PFAS concentration ranged from 0.1 ng/L to 136.274 ng/L in the groundwater, 0.244 ng/L to 59.838 ng/L in the Adyar river, 0.171 ng/L to 60.174 ng/L in the Buckingham canal, 0.137 ng/L to 33.316 ng/L in the Chembarambakkam lake, and 0.136 ng/L to 23.952 ng/L in the raw water of WTP (Figs. 2, 3, 4 and 5). Notably, the two most

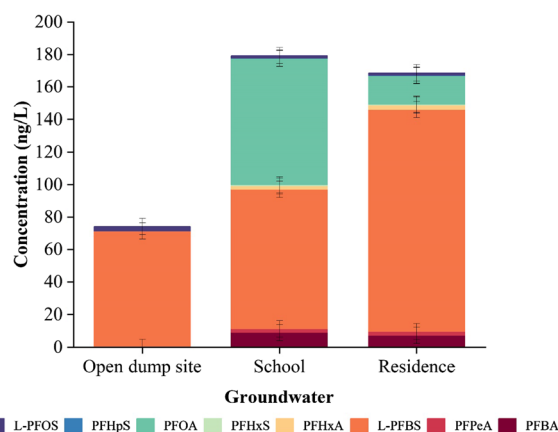


Fig. 2 PFAS concentrations in groundwater. The graph shows the concentrations of the target PFAS in the groundwater samples collected from the Perungudi open dump site, school, and residence

prevalent PFOA and PFBS had a significant rise in their concentrations (8.97 ng/L to 20.40 ng/L and 33.32 ng/L to 48.71 ng/L, respectively) in the treated water compared to the raw water. The target PFAS concentrations detected in the treated water, which is further distributed as drinking water to the city’s residents, match the Indian tap water concentrations (10 ng/L to 100 ng/L) reported by [26]. The highest concentrations of PFBA and PFOA were found in the groundwater from the school (9.09 ng/L and 77.61 ng/L, respectively). L-PFBS and PFHxA were present in the highest concentrations in the residential groundwater (136.27 ng/L and 2.78 ng/L, respectively). L-PFOS and PFHxS at 8.12 ng/L and 1.8 ng/L, respectively, were present upstream of the Adyar river, whereas PFPeA (9.28 ng/L) and PFHpS

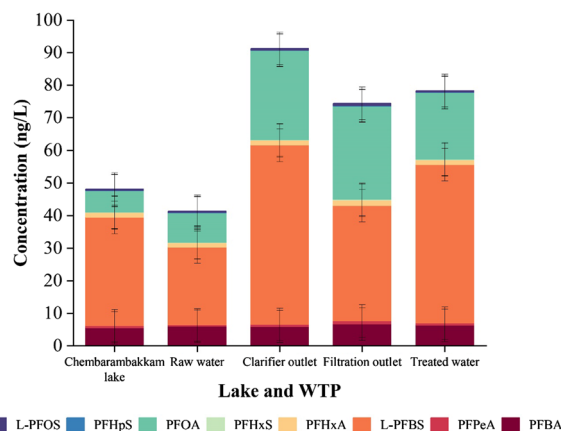


Fig. 3 PFAS concentrations in Chembarambakkam lake and WTP. The graph shows the concentrations of the target PFAS in the surface water sample collected from the Chembarambakkam lake and all stages of WTP

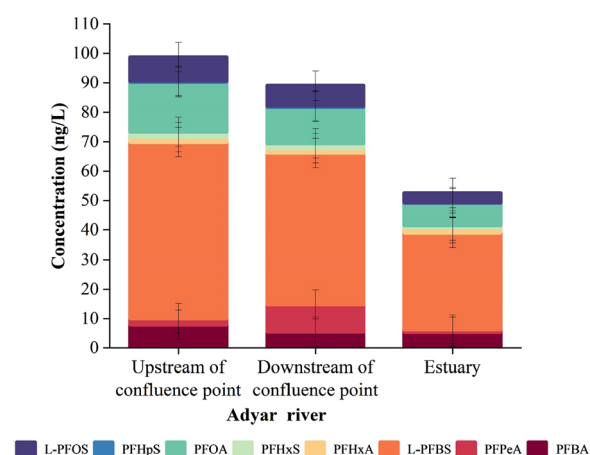


Fig. 4 Target PFAS concentrations in Adyar river. The graph shows the concentrations of the target PFAS in the surface water samples collected from the Adyar river

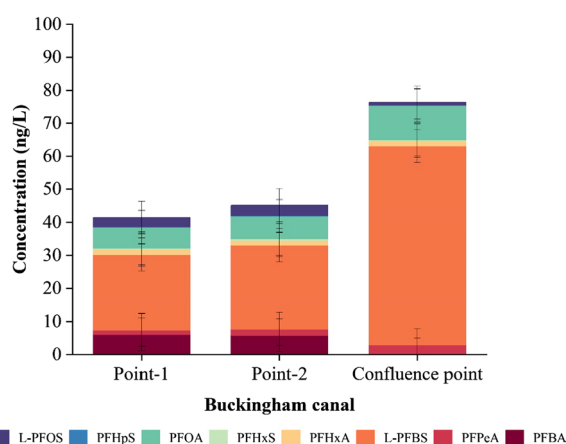


Fig. 5 PFAS concentrations in Buckingham canal. The graph shows the concentrations of the target PFAS in the surface water samples collected from the Buckingham canal

(0.4 ng/L) are present in highest concentrations on the downstream. The concentrations downstream of the Adyar river are relatively lower than upstream, indicating the dilution effect of the Buckingham canal joining the Adyar river at the CP. L-PFBS dominated at all the sampling points (22.85 ng/L and 25.44 ng/L) along the Buckingham canal, including the CP (60.17 ng/L). The Chembarambakkam lake also has L-PFBS (33.32 ng/L) levels higher than the other target PFAS. Additional file 1: Table S4 depicts the concentrations of the eight target PFAS in all fourteen samples. L-PFBS and PFOA are more prevalent in all fourteen samples than the remaining target PFAS. However, L-PFBS is the most common and present in high concentrations compared to the rest. This is primarily due to the hydrophilic nature (log

$K_{oc} = -1.42$ and $\log K_{ow} = -1.82$), making it very mobile and less adsorbent. Additionally, when compared to the US EPA health advisory levels in drinking water, the measured amounts of PFOA (77.61 ng/L), PFBS (136.27 ng/L), and L-PFOS (8.12 ng/L) are each around 19.4×10^3 , 0.068, and 400 times, respectively, the advisory limits of 0.004 ng/L, 2000 ng/L, and 0.02 ng/L [18]. All three compounds possess significant toxicity, as evidenced by their LD50 values of 189 mg/kg, 430 mg/kg, and 251 mg/kg in rats, respectively [27]. According to the US EPA, no regulations exist for the remaining quantified target PFAS. The dominance of short-chain compounds illustrates the paradigm shift from long-chain to short-chain alternatives. The concentrations reported in this study are comparable to those found in Chennai lakes, as written by [28]. As reported, the concentrations of PFOA and PFOS varied from 4 ng/L to 93 ng/L and 3 ng/L to 29 ng/L, respectively. Additionally, according to a related study by [29], the Ganga river included PFHxA and PFBS up to 4.7 ng/L. In contrast, groundwater contained the most significant levels of PFBA and PFBS, up to 9.2 ng/L and 4.9 ng/L, respectively. Similar concentration ranges have been recorded in other international countries, too. Concentrations in the Beijing river, China, have been found to range from 0.04 ng/L to 31.3 ng/L [30]. In urban waters in New Zealand, values between 0.1 ng/L to 13 ng/L were observed by [31]. Even in the United States of America, a mean level of 35.2 ng/L was detected in the riverine waters of Alabama state [32]. According to [33], drinking water in Quebec, Canada, had up to 108 ng/L. These demonstrate that the results of our investigation are consistent with the concentrations reported in other nations as well.

Suspect screening

The suspects based on the qualitative screening were sorted from the raw data with respect to molecular formulae, chemical name, CAS number, m/z, mass, retention time, and abundance. Further shortlisting was done based on the criteria: compound abundance greater than 1000 followed by greater than three times that of the blank. Additional file 1: Table S4.1 through Additional file 1: Table S4.14 of the supplementary material contains the findings of the suspect screening. From this data, the compounds were further narrowed down to the top ten based on their presence in more than 90% of all the samples, as shown in Table 2. The data interpretation was done using Microsoft Excel software. The detailed workflow for data analysis is given in Fig. 6. The suspected compounds were assigned with confidence level 4 (unequivocal molecular formula), as described elsewhere [34]. Confidence level 4 was assigned as this suspect screening was based predominantly on CAS number, molecular

Table 2 Top ten suspects present in the collected samples

S. No	Chemical formula	Chemical name	Applications
1	C ₈ HF ₁₇ O ₃ S	Perfluorooctanesulfonic acid	Medical imaging and implants, flame retardants, electronic devices, electrolyte additives in lithium-ion batteries, surfactants, lubricants, semiconductors, heat transfer applications, etc.
2	C ₈ HF ₁₅ O ₂	Perfluorooctanoic acid	
3	C ₄ HF ₉ O ₃ S	Perfluorobutanesulfonic acid	
4	C ₇ H ₄ F ₁₁ IO	1,1,1,2-tetrafluoro-2-(1,1,2,2,3,3,3-heptafluoropropoxy)-4-iodobutane	
5	C ₁₈ H ₁₈ F ₂₄ N ₃ O ₆ P ₃	Hexakis(2,2,3,3-tetrafluoropropoxy)-phosphazene	
6	C ₈ H ₃ F ₁₅ O ₃	2,2-difluoro-2-[1,1,2,2-tetrafluoro-2-(1,1,2,2,3,3,4,4,4-non-afluorobutoxy) ethoxy] ethanol	
7	C ₅ HF ₁₁	1,1,1,2,2,3,3,4,4,5,5-undecafluoropentane	
8	C ₁₀ H ₂ F ₁₆ O ₄	Perfluorosebacic acid	
9	C ₇ HF ₁₅	1,1,1,2,2,3,3,4,4,5,5,6,6,7,7-pentadecafluoroheptane	
10	C ₁₀ H ₁₂ F ₈	1,1,1,2,2,3,3,4-octa fluoro-7,7-dimethyl oct-4-ene	

Table 2 lists the top ten suspect screening compounds selected based on their frequency of occurrence in more than 90% of the samples with their probable applications in various fields

formulae, and spectral information of the respective compound.

Risk assessment

Risk assessment for probable non-carcinogenic effects on humans was also carried out in the present study for the two most prevalent PFAS in all the samples with the highest detected concentrations in the collected samples, i.e., L-PFBS (136.27 ng/L) and PFOA (77.61 ng/L). Exposure through drinking water ingestion for an adult weighing 60 kg and a child weighing 10 kg at water intake rates of 2 L/d and 1 L/d, respectively [35], were considered for the risk assessment calculations. The CDI and HI were calculated using Eqs. 1 and 2, respectively [36]. Chronic reference doses of 0.0003 mg/kg-day and 0.00002 mg/kg-day for L-PFBS and PFOA, respectively [37] were used to calculate HI. The health risks were categorized using a well-established system: high risk (HI > 1), moderate risk (0.1 ≤ HI < 1), and low risk (HI < 1) [38]. The calculated CDI values for L-PFBS and PFOA are 4.542 × 10⁻⁶ mg/kg-day and 2.587 × 10⁻⁶ mg/kg-day, respectively, for an adult. Similarly, for a child, calculated CDI values for L-PFBS and PFOA are 13.627 × 10⁻⁶ mg/kg-day and 7.761 × 10⁻⁶ mg/kg-day, respectively. Subsequently, the calculated HI (adult) for L-PFBS and PFOA is 0.015 and 0.129, respectively, and for a child, the values are 0.045 and 0.388, respectively. The HI values indicate that there is currently low to moderate risk involved through ingestion of PFAS-contaminated drinking water. The risk is higher in the case of children compared to adults. These calculations are limited to only two individual compounds, and the cumulative risk for all PFAS can be higher. Although the detected concentrations do not immediately affect human health, it is necessary

to rigorously monitor PFAS across multi-environmental matrices to establish a pathway for regulations and policymaking.

$$\text{Chronic daily intake, } CDI \left(\frac{\text{mg}}{\text{kg} \cdot \text{day}} \right) = \frac{C \left(\frac{\text{mg}}{\text{L}} \right) \times CR \left(\frac{\text{L}}{\text{d}} \right)}{BW \text{ (kg)}} \quad (1)$$

$$\text{Hazard index, } HI = \frac{CDI}{RfD} \quad (2)$$

C—Concentration (mg/L).

CR—Contact rate (1 L/day for a child, 2 L/day for an adult).

BW—Body weight (10 kg for a child, 60 kg for an adult).

RfD—Reference dose (mg/kg-day).

Discussion

Some significant sources contributing to PFAS in the environment are landfills/open dump sites, wastewater treatment plants, industrial emissions/effluent discharges, and the use of AFFF for firefighting. Being a big metropolis, Chennai produces a lot of solid waste daily, which is disposed of in the open dump sites at Perungudi and Kodungaiyur. In the Perungudi open dump site alone, about 4500 tons of municipal solid waste is disposed of daily [39]. The prevalent presence of PFAS in groundwater at the Perungudi open dump site and its surroundings primarily stems from their ubiquitous use in consumer products like non-stick cookware, cleaning agents, fabrics, and personal care products [40]. These products release PFAS into the soil at dump sites over time, ultimately contaminating leachate and groundwater [41]. Domestic wastewater further contributes to the environmental burden

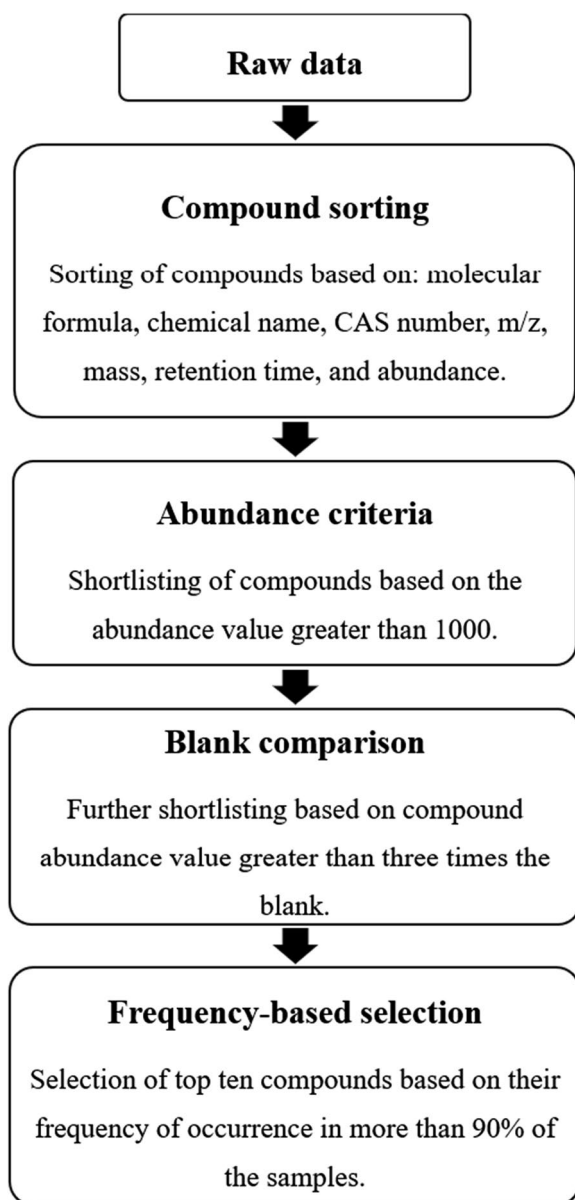


Fig. 6 Workflow for suspect screening data analysis. The flowchart depicts the procedure for analyzing the collected samples' qualitative screening data

through the ongoing use of PFAS-containing products. This explains the presence of PFAS in the Adyar river and Buckingham canal, where untreated domestic wastewater is discharged. Many industries, including polymer manufacturing, are situated close to the Chembarambakkam lake, which explains the presence of the PFAS in the lake and subsequently in the WTP at substantial amounts, especially L-PFBS and PFOA which are used in many consumer and industrial applications such as food packaging, fluoropolymers, and

oil/stain/water-repellent coatings [5]. Also, it has been observed that the concentrations of all eight target PFAS increased in the range of 5 to 103% in the treated water of the WTP compared to the raw water. Conventional water treatment processes can sometimes lead to increased levels of PFAS in treated water compared to the raw water. This phenomenon, observed in studies like [42], is likely due to the presence of unidentified precursors that transform into more stable PFAS end products during treatment. Similar observations have been made in conventional wastewater treatment plants [43, 44]. Here, known precursors like FTSs, FTOHs, FTOs, FTALs, FTCAs, FASAs (PFOA), FASEs (N-MeFOSE, N-EtFOSE), PAPs, PFIs, and PFBs [11, 45], can transform into PFCAs and PFSA during treatment. This transformation creates more stable and persistent forms of PFAS, thereby increasing their concentrations in treated water compared to raw water. Several factors influence the type and rate of these transformations, including the presence of other contaminants, water treatment plant operating conditions (pH, temperature, technology used), and even the activity of microbes within the treatment system [11]. Some common transformation pathways include electrochemical fluorination, biodegradation, and free-radical oxidation [46, 47]. Understanding these transformation processes is crucial for effectively managing PFAS contamination in water treatment plants and ensuring the safety of treated water.

This shows that an advanced polishing treatment system is necessary to eliminate these chemicals from the water systems as the conventional treatment is ineffective rather increasing the concentrations [46]. Also, this is consistent with the findings reported by [48] and [49]. Also, the HDPE/PVC pipelines, which are mainly utilized in water conveyance systems [50], may have the potential to contaminate the treated water with PFAS while transporting water from the WTP to the Chennai city's distribution systems. From dump sites to groundwater, cookware to wastewater, these persistent chemicals have infiltrated every facet of the surroundings. Also, the risk assessment has shown a low to moderate risk by exposure through contaminated drinking water ingestion for both adults and children, with the children being more vulnerable.

Conclusions

Two short-chain PFCAs (PFHxA and PFPeA) and PFSA (L-PFBS and PFBA), one long-chain PFCA (PFOA), and three long-chain PFSA (PFHpS, L-PFOS, and PFHxS), i.e., total eight target PFAS, were quantified in various water samples collected from Chennai, Tamil Nadu, India. Concentrations of PFBA, L-PFBS, PFHxA, and

PFOA were found to be predominant in groundwater, while PFPeA, PFHpS, PFHxS, and L-PFOS were found to be dominant in surface waters. It is necessary to have an advanced polishing treatment system that can remove PFAS from water because conventional water treatment does not reduce these chemicals, rather, makes them more prevalent. The PFOA and PFOS concentrations are much higher than the US EPA drinking water health advisory levels. The results depict the switch from using long-chain compounds to short-chain alternatives. Suspect screening revealed abundant presence of numerous precursors and unidentified fluorinated compounds in the samples, which require additional investigation to ascertain the degree of PFAS contamination in the Chennai waters. Alternative approaches, such as the estimation of total adsorbable/extractable organic fluorine through combustion ion-chromatography [51, 52] and total oxidizable precursor assay [53], can also be adapted to screen the water samples for overall PFAS assessment. Moreover, because there are so many PFAS, assessing each can be difficult, costly, and time-consuming. While the said methods directly measure total organic fluorine, they can estimate PFAS levels because PFAS contain fluorine. These methods would be an easy and quick way to screen for analyzing the sum of the various precursors and unknown fluorinated compounds. They offer a comprehensive evaluation of PFAS contamination rather than focusing on individual chemicals.

The occurrence of PFAS in Chennai waters is thus evident from the results obtained in the present study. Industrial emissions, untreated domestic wastewater discharge, and open dump sites have been suspected as significant sources of contamination in the Chennai waters. This highlights the necessity for more awareness and additional research into the spread of PFAS in Indian multi-environmental media.

Abbreviations

°C	Degree celsius
µg/mL	Microgram per milliliter
µL	Microliter
µm	Micrometer
ACS	American chemical society
AFFF	Aqueous film-forming foam
APHA	American Public Health Association
CAS	Chemical abstracts service
CDI	Chronic daily intake
CIC	Combustion ion chromatography
cm	Centimeter
CP	Confluence point
D/S	Downstream
eV	Electron volt
FASA	Perfluoroalkane sulfonamide
FASE	N-Alkyl perfluoroalkane sulfonamidoethanol
FTAL	Fluorotelomer aldehyde
FTCA	Fluorotelomer carboxylic acid
FTO	Fluorotelomer olefin
FTOH	Fluorotelomer alcohol
FTS	Fluorotelomer sulfonate

g/L	Gram per liter
GenX	Hexafluoropropylene oxide dimer acid
HDPE	High-density polyethylene
HI	Hazard index
HPLC	High-performance liquid chromatography
ICP-OES	Inductively coupled plasma–optical emission spectrometer
kcal/mol	Kilo calorie per mole
km	Kilometer
K _{oc}	Organic carbon _{water} partition coefficient
K _{ow}	Octanol _{water} partition coefficient
L/d	Liters per day
L/min	Liters per minute
LC–MS	Liquid chromatography–mass spectrometry
LC-PFCAs	Long-chain perfluoro carboxylic acids
LC-QTOF-MS	Liquid chromatography quadrupole time-of-flight mass spectrometry
LD	Lethal dose
LOD	Limit of detection
LOQ	Limit of quantification
L-PFBS	Linear perfluorobutanesulfonic acid
L-PFOS	Linear perfluorooctanesulfonic acid
m/z	Mass-to-charge ratio
mg/kg	Milligram per kilogram
mg/kg-day	Milligrams per kilogram day
min	Minute
mL	Milliliter
MLD	Million liters per day
mm	Millimeter
mMol/L	Millimoles per liter
N-EtFOSE	2-(N-ethyl perfluorooctane sulfonamido) ethanol
ng/g	Nanogram per gram
ng/L	Nanogram per liter
ng/mL	Nanogram per milliliter
N-MeFOSE	N-methyl perfluorooctane sulfonamidoethanol
PAPs	Polyfluoroalkyl phosphate esters
PDA	Photodiode array
PFAS	Per- and polyfluoroalkyl substances
PFB	Perfluorinated bromide
PFBA	Perfluorobutanoic acid
PFC	Perfluorinated compound
PFCA	Perfluoroalkyl carboxylic acid
PFETs	Perfluoroethanesulfonic acid
PFHpA	Perfluoroheptanoic acid
PFHpS	Perfluoroheptanesulfonic acid
PFHxA	Perfluorohexanoic acid
PFHxS	Perfluorohexanesulfonic acid
PFIs	Perfluorinated iodides
PFOA	Perfluorooctanoic acid
PFOSA	Perfluorooctanesulfonamide
PFOSF	Perfluorooctanesulfonyl fluoride
PFPeA	Perfluoropentanoic acid
PFPrA	Perfluoropropionic acid
PFPrS	Perfluoropropanesulfonic acid
PFSA	Perfluorosulfonic acid
pg/L	Picogram per liter
POP	Persistent organic chemicals
ppq	Parts per quadrillion
ppt	Parts per trillion
psig	Pounds per square inch gauge
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl chloride
RfD	Reference dose
S/N	Signal to noise
U/S	Upstream
US EPA	United States Environmental Protection Agency
WAX	Weak anion exchange
WTP	Water treatment plant

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s12302-024-00881-1>.

Additional file 1. Details regarding sampling points, PFAS analytical standards, basic water quality parameters, quantitative and qualitative PFAS data of the collected samples.

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Author contributions

GVK contributed to conceptualization, methodology, analysis, writing-original draft; IMN was involved in writing—review and editing. All authors reviewed the manuscript.

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Data availability

All data generated or analyzed during this study are included in this published article (and its supplementary information file).

Declarations

Competing interests

The authors declare no competing interests.

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