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MORALITY BEFORE KNOWLEDGE

Baseline study of per- and polyfluoroalkyl substances (PFAS) occurrence in surface raw water and treated drinking water

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ABSTRACT

Background: Per- and polyfluoroalkyl substances (PFAS) are emerging contaminants that have become a global concern due to their adverse environmental and health impacts. However, information regarding PFAS contamination in river-derived drinking water systems in developing countries, including Indonesia, remains limited. This study aimed to analyze 19 PFAS compounds in raw water, treated drinking water, and Reverse Osmosis (RO) reject water from the X DWTP, Jakarta, Indonesia, and evaluate its potential human risk and mitigation strategies. **Methods**: Water samples were analyzed using LC-MS/MS. **Findings:** Nine PFAS detected with ∑PFAS concentrations reaching 758.94 and 1219.35 ng/L in raw and drinking water, respectively. The RO unit effectively removed long-chain PFAS compounds, particularly PFOS and PFOA, highlighting the importance of advanced treatment technologies in reducing potential human exposure risks. In contrast, PFBA remained substantially high in treated drinking water and exceeded the drinking water threshold of the European Union (EU). **Conclusion**: These findings emphasize the importance of strategic PFAS management through source-control mitigation, establishment of drinking water standards, and implementation of Best Available Techniques (BAT). **Novelty/Originality of this article:** This study provides the first baseline data on PFAS contamination in Jakarta's surface water-derived drinking water supporting future PFAS monitoring and mitigation efforts.

KEYWORDS: drinking water; PFAS; reverse osmosis; surface water.

1. Introduction

Per- and polyfluoroalkyl substances (PFAS) have become a global concern due to their adverse impacts on the environment and human health. PFAS are synthetic chemicals that were first be produced in the 1930s and were widely used in various industries from the 1940s to the 1950s, including firefighting foams, aerospace technologies, and consumer products (Brennan et al., 2021). Recently, PFAS have received increasing attention because of their high environmental persistence. The strong chemical stability of PFAS makes these compounds highly resistant to natural degradation (Brunn et al., 2023; Rahman et al., 2014). Consequently, PFAS have been detected globally in various environmental compartments, including water, soil, sediment, and air (O'Sullivan Bakshi et al., 2025; Zhong et al., 2025).

Aquatic environments are among the most vulnerable environmental compartments to PFAS contamination. Once released into aquatic systems, PFAS can migrate over long distances and contribute to global contamination. Numerous studies have reported the occurrence of PFAS in surface waters, sediments, and aquatic organisms across the United

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States, Europe, Africa, Asia, and even the Arctic region (Ghisi et al., 2019; International Pollutants Elimination Network (IPEN), 2019; Muir et al., 2019; Omotola et al., 2024; Pétré et al., 2022; Zarębska et al., 2024). In North America, PFAS contamination has been identified in river surface waters and sediments in Alabama and Nevada (Bai & Son, 2021; Viticoski et al., 2022), as well as in fish from multiple freshwater systems (Stahl et al., 2023). Similar contamination patterns have been observed in northern waters, the Atlantic Ocean, the Southern Ocean, and several river systems across Europe (Ahrens et al., 2010; Loos et al., 2009). PFAS have also been detected in aquatic environments in Africa and Asia, including Lake Victoria in East Africa and major river systems such as the Pearl River and Yangtze River in China (Arinaitwe et al., 2020; So et al., 2007). The occurrence of PFAS in aquatic environments, particularly rivers, may lead to human exposure through the consumption of aquatic organisms and drinking water derived from PFAS-contaminated surface waters (Brunn et al., 2023).

Consumption of PFAS-contaminated drinking water is considered one of the primary pathways of PFAS exposure in humans (Shen & Zhang, 2025). Perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) concentrations in rivers worldwide were several times higher than the United States Environmental Protection Agency (US EPA) health advisory level of 70 ng/L for lifetime exposure through drinking water (Podder et al., 2021). Other studies have also reported PFAS contamination in surface waters used as drinking water sources at concentrations exceeding the safety thresholds established by the United States Environmental Protection Agency (US EPA) (Duru et al., 2026; Stefano et al., 2023). If continuously accumulated in the human body, PFAS may cause prolonged adverse effects and may reduce human quality of life.

The Agency for Toxic Substances and Disease Registry (ATSDR) has identified several potential health impacts of PFAS exposure, including altered cholesterol and liver enzyme levels, changes in birth weight, reduced immune response to certain vaccines, increased risk of preeclampsia in pregnant women, and elevated risks of certain cancers such as kidney and testicular cancer (Petali, 2023). Other health effects associated with PFAS exposure include liver damage, immune system dysfunction, infertility issues, neurotoxicity, and other chronic health problems (Brunn et al., 2023; Liang et al., 2023). The adverse effects of PFAS on the environment and health have attracted worldwide attention. Various health and environmental experts continue to review PFAS pollution and its impact on the environment and humans (Evich et al., 2022; Fenton et al., 2021; Omotola et al., 2024).

Various international organizations and countries have implemented regulatory measures to control and minimize human exposure to PFAS emissions. The U.S. Environmental Protection Agency (EPA) has established drinking water health advisories of 0.004 ng/mL for PFOA and 0.02 ng/mL for PFOS, reflecting the growing recognition of their extreme toxicity and persistence (United States Environmental Protection Agency (US EPA), 2022). PFOS and PFOA have also been listed as Persistent Organic Pollutants (POPs) under the Stockholm Convention, and their production and use are now subject to strict limitations (United Nations Environment Programme (UNEP), 2009, 2019). The European Food Safety Authority (EFSA) has set a tolerable weekly intake (TWI) of 4.4 ng/kg body weight for the combined exposure to PFOS, PFOA, PFNA, and PFHxS to protect human health from long-term accumulation (Schrenk et al., 2020). Despite these international efforts, developing countries, including Indonesia, still lack comprehensive monitoring data and regulatory frameworks to address PFAS contamination.

Urban rivers in tropical megacities may be particularly vulnerable to PFAS contamination due to dense populations, industrial activities, domestic wastewater discharge, and limited wastewater treatment infrastructure. Despite these potential risks, the occurrence of PFAS in tropical urban drinking water systems remains poorly understood, particularly in Southeast Asian countries such as Indonesia. The lack of monitoring data creates challenges in evaluating human exposure risks and developing appropriate mitigation strategies. Evidence of PFAS contamination in Indonesia has been reported, particularly in the Jakarta Bay area. A 2011 study found that sediment samples collected from Jakarta Bay in 2004 contained detectable levels of PFOA and PFOS, with PFOA

concentrations reaching 6.1 µg/kg dry weight, ten times higher than the highest levels previously observed in San Francisco Bay, United States, and PFOS concentrations ranging from 0.9 to 3.7 µg/kg dry weight (Ismawati & Digangi, 2019). These findings suggest that PFAS contamination in Jakarta Bay may originate from industrial and domestic wastewater discharges transported through the city's river systems. The occurrence of PFAS in Jakarta Bay also indicates the potential presence of PFAS contamination in Jakarta rivers, as PFAS contamination in marine environments is commonly associated with riverine inputs (Du et al., 2022).

The Mookervart River is one of the rivers in Jakarta that may have been contaminated by PFAS, particularly because industrial activities dominate part of the land use surrounding the river. Industrial wastewater is recognized as one of the primary sources of PFAS contamination in river systems (Lee et al., 2025). The Mookervart River is also used as a raw water source for drinking water production. Surface water from the Mookervart River is treated into drinking water by a drinking water treatment plant (X DWTP) in Jakarta using reverse osmosis (RO) technology. RO is recognized as one of the most effective technologies for the removal of PFAS from water, with removal efficiencies exceeding 90% and potentially approaching 99% (Liu et al., 2022; Mastropietro et al., 2021). However, the effectiveness of RO may vary depending on several factors, including PFAS type, membrane quality, raw water characteristics, operational conditions, and membrane fouling (Mastropietro et al., 2021). Therefore, monitoring PFAS contamination in treated drinking water from the X DWTP is important as part of efforts to mitigate public PFAS exposure risks.

Despite growing global concern regarding PFAS contamination, monitoring data and regulatory frameworks in developing countries, including Indonesia, remain limited. Previous studies in Indonesia have mainly focused on PFAS contamination in marine sediments, particularly in Jakarta Bay. However, information regarding PFAS occurrence in river-derived drinking water systems is still unavailable. In addition, no study has evaluated the simultaneous occurrence of PFAS in raw water and treated drinking water in Indonesia. Therefore, this study aims to analyze 19 PFAS compounds in raw water, treated drinking water, and RO reject water from the X DWTP, Jakarta, Indonesia. This study provides the first baseline data on PFAS contamination in river-derived drinking water systems in Indonesia and is expected to support future PFAS monitoring and mitigation efforts.

2. Methods

2.1 Study area

This study was conducted at the X Drinking Treatment Water Plant (X DWTP) in Jakarta, Indonesia. The facility supplies drinking water to one resident in Jakarta. Raw water for the treatment plant is obtained from the Mookervart Reservoir, which receives surface water from the Mookervart River and domestic wastewater discharges from surrounding urban areas. The Mookervart River is located Jakarta's densely populated domestic and partially industrialized areas, making it potentially vulnerable to PFAS contamination from domestic and industrial activities. Industrial wastewater is recognized as one of the major sources of PFAS contamination in aquatic environments. In addition, the use of the river as a drinking water source increases the potential risk of human exposure to PFAS contamination. The drinking water treatment process at the facility includes several treatment stages, including moving bed biofilm reactor (MBBR), aeration, clarification, ultrafiltration (UF), and reverse osmosis (RO) as the final treatment stage. In this study, raw water, treated drinking water, and RO reject water samples were analyzed to evaluate the occurrence of PFAS before and after treatment, as well as PFAS removal associated with the RO process.

2.2 Sample collection

Sampling was conducted in October 2025. Duplicate grab samples were collected for each raw water, drinking water, and reverse osmosis reject. Approximately 100 mL of each water sample was collected and stored in polypropylene (PP) bottles. PP materials were used to minimize the potential risk of PFAS contamination, while PTFE- or Teflon-based materials were strictly avoided throughout the sampling and storage procedures. No bottle pre-cleaning procedure was applied. New sample bottles were directly used to minimize the risk of cross-contamination during pre-cleaning. After collection, all samples were maintained at temperatures ≤4 °C and transported to the laboratory for pretreatment and subsequent analysis within 14 days.

2.3 Chemicals and reagents

All reagents used in this study were of LC–MS grade. Methanol (CH_3OH), ammonium acetate (CH_3COONH_4), and ammonia solution (NH_4OH) were purchased from Sigma-Aldrich (St. Louis, MO, USA). Ultrapure water (specific resistance 18 $M\Omega \cdot cm^{-1}$ at 25 °C) was produced using a Milli-Q system. Certified reference standards and isotopically labeled internal standard mixture for nineteen PFAS compounds, including perfluorobutanoic acid (PFBA), perfluoropentanoic acid (PFPeA), perfluorohexanoic acid (PFHxA), perfluoroheptanoic acid (PFHpA), perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA), perfluorodecanoic acid (PFDA), perfluoroundecanoic acid (PFUnDA), perfluorododecanoic acid (PFDoA), perfluorotridecanoic acid (PFTrDA), perfluorotetradecanoic acid (PFTeA), perfluorobutanesulfonic acid (PFBS), perfluorohexanesulfonic acid (branched, PFHxS), perfluoroheptanesulfonic acid (PFHpS), perfluorooctanesulfonic acid (branched, PFOS), perfluorodecanesulfonic acid (PFDS), 6:2 fluorotelomer sulfonic acid (6:2 FTS), 8:2 fluorotelomer sulfonic acid (8:2 FTS), and perfluorooctane sulfonamide (FOSA), were purchased from Wellington Laboratories (Ontario, Canada).

2.4 Sample preparation

Water samples were analyzed before LC-MS/MS analysis. Solid-phase extraction (SPE) was carried out using EVOLUTE® EXPRESS WAX cartridges (150 mg, 6 mL; Biotage, Uppsala, Sweden). Before sample loading, the cartridges were conditioned sequentially with 6 mL of 2% ammonia in methanol, followed by 6 mL of methanol and 6 mL of reagent water. Subsequently, 2 mL of 0.1% formic acid was added and soaked for 2 min. 10 mL of the water sample was added to the cartridge. The cartridges were rinsed with 6 mL of water and dried for 15 min after sample loading. Elution was performed using 6 mL methanol and 6 mL 2% ammonia in methanol. The collected eluate was concentrated to approximately 0.3 mL under a nitrogen stream at temperatures below 60 °C, reconstituted in 1 mL of 50% (v/v) methanol, filtered through a 0.22 μm PP membrane, and transferred into 1.5 mL PP vials prior to LC–MS/MS analysis.

2.5 Analytical methods and data analysis

PFAS analysis was performed using liquid chromatography–tandem mass spectrometry (LC–MS/MS). Chromatographic separation was performed using on an Agilent 1260 Infinity II system coupled with Agilent 6495C Triple Quadrupole mass spectrometer. The column used in this analysis is Agilent SB-C18 column (1.8 μm, 100 × 4.6 mm). The column temperature was maintained at 50 °C, and the injection volume was set at 10 μL. 2 mM ammonium acetate in water was used for mobile phase A and 2 mM ammonium acetate in methanol was used for mobile phase B. LC flow rate was delivered at 0.5 mL/min. The initial condition was started at 0% B and maintained for 1 minutes, then increased to 50% from 1 to 6 minutes, then increased to 80% from 6 to 15 minutes, and

increased again to 100% from 15 to 24 minutes. %B then decreased to 0% at 24.1 and was maintenated at 0% until 35 minutes for column re-equilibration. The MS system was operated in negative electrospray ionization (ESI−) mode using multiple reaction monitoring (MRM) mode. The MRM parameter are listed in Table S1. The following source parameters were set: capillary voltage of 3,500 V, drying gas flow of 13 L/min at 200 °C, sheath gas flow of 11 L/min at 400 °C, and nebulizer pressure of 20 psi.

A quality control (QC) procedure was conducted to ensure data accuracy and reliability. Calibration curves for all target analytes showing excellent linearity (R^2 > 0.995 for all analytes) (Table S2). The Method limit detection (MDL) ranged from 0.004 to 1 ng/mL, as shown in Table S3. Recovery was evaluated to assess the sample preparation and analytical procedure efficiency. The recovery values for the target PFAS compounds ranged from 85.5% to 198.0%, with an overall average recovery of 113.0% (Table S4). No target PFAS were detected in the blank samples, indicating no contamination during sampling or analysis.

Data analysis was conducted using descriptive statistical methods to compare the PFAS concentrations in raw water, treated drinking water, and reverse osmosis (RO) reject water samples. The potential risks to public health were subsequently evaluated by comparing PFAS concentrations detected in raw water and treated drinking water with international drinking water standards established by the United States Environmental Protection Agency (US EPA) (2024) National Primary Drinking Water Regulation (NPDWR) and the EU Drinking Water Directive (2020/2184). Potential health impacts associated with PFAS exposure were assessed through a comprehensive literature review. Furthermore, strategic approaches for mitigating the environmental and health impacts of PFAS contamination were developed based on literature studies to provide scientific recommendations to support future PFAS management and regulatory efforts in Indonesia.

3. Results and Discussion

3.1 PFAS analysis of raw water, drinking water, and reverse osmosis rejects

In this study, raw water, treated drinking water, and RO reject water samples were collected within a relatively short time interval; therefore did not represent the same batch throughout the treatment process. Thus, the treated drinking water analyzed in this study did not originate from the raw water sampled at the same time. This condition may cause the calculated RO removal efficiency to be either higher or lower than the actual performance. Therefore, the removal efficiency reported in this study can be interpreted as a general representation rather than an absolute measure of the RO performance at the X DWTP.

A total of 19 PFAS compounds were analyzed in raw water, treated drinking water, and RO reject water samples. Nine compounds, namely, PFBA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFBS, PFOS, and 6:2 FTS, were detected, while the remaining 10 compounds were below the quantification detection limit (QDL). The average total PFAS concentrations in raw water, treated drinking water, and RO reject water were 758.92 ng/L, 1219.35 ng/L, and 847.98 ng/L, respectively. The composition of the PFAS compounds in each sample is presented in Fig. 1.

The PFAS concentrations detected in the raw water and treated drinking water in this study were substantially higher than those reported in surface water sources from other countries. The total PFAS concentrations detected in the surface water of the Gunpowder River ranged from 6.6–18.4 ng/L, with short-chain PFAS dominating the samples (Duru et al., 2026). In Brazilian river surface waters, total PFAS concentrations ranged from 11–17 ng/L (Stefano et al., 2023). In contrast, the total PFAS concentration detected in the treated drinking water in this study reached 1219.35 ng/L. The results showed that total PFAS concentrations were higher in treated drinking water than in raw water, primarily due to the extremely high PFBA concentration detected in treated drinking water (1202.26 ng/L). Nevertheless, long-chain PFAS compounds (PFHxA, PFHpA, PFOA, and PFNA) were detected

at very low concentrations in treated drinking water (PFOS). These findings indicate differences in the effectiveness of the RO system at the X DWTP in removing PFAS compounds.

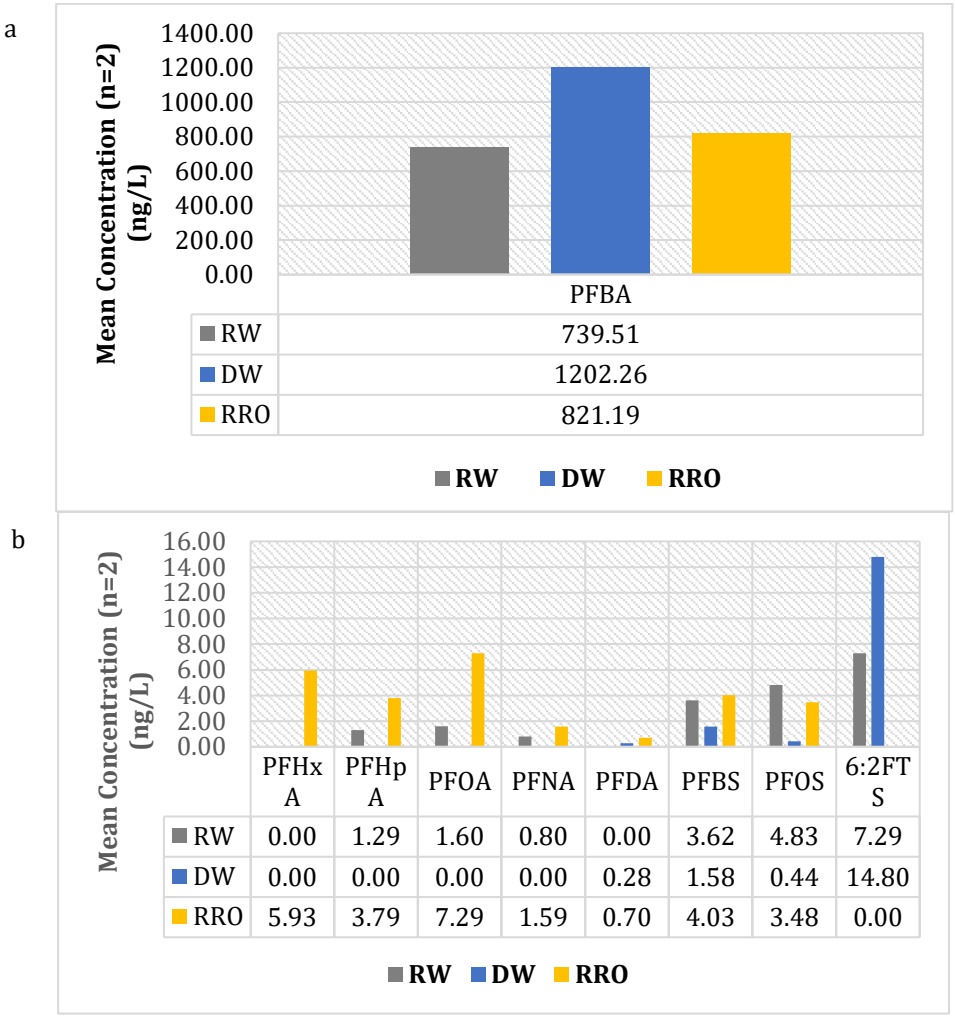

Fig. 1. Average concentrations of (a) PFBA and (b) PFHxA, PFHpA, PFOA, PFNA, PFDA, PFBS, PFOS, and 6:2 FTS in raw water (RW), treated drinking water (DW), and RO reject water (RRO) samples

The RO unit at the X DWTP effectively removed long-chain PFAS compounds. PFHpA, PFOA, and PFNA were detected in raw water at concentrations of 1.29 ng/L, 0.80 ng/L, and 1.6 ng/L, respectively, but were not detected in treated drinking water, indicating that the RO process efficiently removed these compounds. In addition, PFOS, which was detected at 4.83 ng/L in raw water, was only detected at 0.44 ng/L in treated drinking water, suggesting high removal efficiency. Similarly, PFDA was detected only at a low concentration (0.28 ng/L) in treated drinking water. Although PFDA was not detected in raw water, its presence in RO reject water suggests that the compound may have been present in raw water at concentrations below the detection limit. A similar pattern was observed for PFHxA, which was detected in RO reject water but not in treated drinking water, indicating that PFHxA was successfully removed during the treatment process. In contrast, the RO system at the Mookervart facility was less effective in removing short-chain PFAS compounds, such as PFBA, PFBS, and 6:2 FTS.

PFBA was the dominant PFAS compound detected in this study, with average concentrations of 739.51 ng/L in raw water, 1202.26 ng/L in treated drinking water, and 821.19 ng/L in RO reject water. The PFBA concentration detected in treated drinking water was substantially higher than that reported in treated drinking water derived from the Mississippi River, United States (55.4 ng/L) (Boone et al., 2014), indicating relatively high PFBA contamination in the study area. The elevated PFBA concentration in treated drinking

water was likely associated with the high PFBA concentration in the raw water. In this study, raw water consisted of a mixture of water from the Mookervart River and domestic wastewater, while the Mookervart River receives inputs from both domestic and industrial activities. Elevated PFBA concentration may be associated with the global transition from long-chain to short-chain PFAS as an alternative compound (Cookson & Detwiler, 2022; Li & MacDonald Gibson, 2022; Zhao et al., 2016). Although PFBA was detected in all sample types, its concentration remained high in the treated drinking water, suggesting that the treatment system had limited effectiveness in removing this compound. The relatively low removal efficiency of PFBA is likely related to its characteristics as a short-chain PFAS compound with high polarity and low adsorption affinity, making it more difficult to remove than long-chain PFAS compounds (Zhang et al., 2025b).

Similar conditions were observed for other short-chain PFAS compounds, including PFBS and 6:2 FTS. PFBS was detected in raw water at an average concentration of 3.62 ng/L and remained detectable in treated drinking water at 1.58 ng/L, although part of the compound was removed and detected in RO reject water at 4.03 ng/L. This finding indicates that the RO process had limited effectiveness in removing PFBS. Meanwhile, 6:2 FTS exhibited even lower removal efficiency, as indicated by its high concentrations in raw and treated drinking water, reaching 7.29 and 14.8 ng/L, respectively, and was not detected in RO-rejecting water. These findings suggest that 6:2 FTS may not have been effectively retained by the RO membrane and therefore passed into the treated drinking water.

Reverse osmosis is considered one of the most effective technologies for removing PFAS, including both long-chain and short-chain PFAS compounds (Wang et al., 2024a). The relatively low removal efficiency of short-chain PFAS may be influenced by several factors, including the following: (1) molecular size, where short-chain PFAS compounds such as PFBA and PFBS are more likely to pass through RO membranes due to their smaller molecular size (Mastropietro et al., 2021); and (2) the potential decline in RO membrane performance during long-term operation and annual usage.

Overall, the results indicate that the RO unit effectively removed long-chain PFAS compounds; however, its removal efficiency for short-chain PFAS remained relatively limited. Further studies are needed to identify the factors affecting the low removal efficiency of PFBA, PFBS, and 6:2 FTS, including investigations incorporating sampling retention time, operational conditions, repeated measurements at different sampling times and different locations, and more comprehensive evaluations of RO performance. Although this study primarily focused on assessing PFAS contamination in drinking water, PFAS detection in both raw and treated water highlights the potential risk of human exposure. Therefore, comparison with international drinking water standards is essential for evaluating drinking water safety and to provide context for potential public exposure risks to PFAS.

3.2 Evaluation of PFAS in drinking water based on international regulatory standards and potential human exposure effects

In this study, PFAS concentrations detected in raw water and drinking water were evaluated based on two international regulatory frameworks that comprehensively regulate PFAS in drinking water: the European Union Drinking Water Directive (2020/2184) and the United States Environmental Protection Agency (US EPA) National Primary Drinking Water Regulation (2024). The European Union regulates PFAS through two main parameters: the sum of 20 PFAS (100 ng/L) and total PFAS (500 ng/L) (European Union, 2020). Meanwhile, the United States Environmental Protection Agency (US EPA) has established Maximum Contaminant Levels (MCLs) of 4 ng/L for both PFOA and PFOS, and 10 ng/L for PFHxS, PFNA, and HFPO-DA (GenX) (United States Environmental Protection Agency (US EPA), 2022). These science-based regulatory thresholds were used as references to evaluate the safety of PFAS contamination in treated drinking water. Table 1 compares the PFAS concentrations in raw water and treated drinking water with the EU and US EPA standards.

Table 1. Comparison of PFAS concentrations in raw water and treated drinking water from the X DWTP with international drinking water standards

Regulation	Regulated compounds	Standard value (ng/L)	PFAS in the raw water	PFAS in drinking water
US EPA (2024) – National Primary Drinking Water Regulation (NPDWR)	PFOA	4	1.60	0
	PFOS	4	4.83	0.44
	PFHxS	10	0.00	0
	PFNA	10	0.00	0
	HFPO-DA (GenX)	10	0.00	0
EU (2020/2184) – Drinking Water Directive	Sum of the 20 PFAS	100 ng/L	751.65	1204.56
	Total PFAS	500 ng/L	758.94	1219.35

Comparison with the US EPA drinking water standards indicated that PFAS concentrations in treated drinking water were within the safe category, whereas PFOS concentrations in raw water exceeded the regulatory threshold. PFOS was detected in both raw and treated drinking water; however, its concentration in treated drinking water was relatively low (0.44 ng/L) compared with that in raw water (4.83 ng/L). Similarly, PFOA and PFNA detected in raw water were not detected in treated drinking water, indicating that RO treatment effectively reduced the risk of human exposure to these compounds. Conventional drinking water treatment processes are generally ineffective in removing PFAS (Xiao et al., 2023b), highlighting the importance of advanced treatment technologies, such as RO, for PFAS mitigation. Despite the use of advanced treatment technologies, removal effectiveness remains an important consideration. Comparison with the European Union standards showed that PFAS concentrations in treated drinking water exceeded the regulatory limits, primarily due to the extremely high PFBA concentrations detected in both raw and treated drinking water.

The EU Drinking Water Directive (2020/2184) establishes two main regulatory parameters for PFAS in drinking water: 100 ng/L for the *sum of 20 PFAS* and 500 ng/L for *total PFAS*. The *sum of 20 PFAS* categories includes 20 regulated PFAS compounds, of which PFBA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFBS, and PFOS were detected in this study. The *sum of 20 PFAS* concentrations reached 751.65 ng/L and 1204.56 ng/L in raw water and treated drinking water, respectively, while the *total PFAS* concentrations were 758.94 ng/L and 1219.35 ng/L, respectively. Both raw water and treated drinking water exceeded the EU regulatory limits for both categories.

These exceedances were primarily attributed to the extremely high PFBA concentrations detected in the samples. Without considering PFBA, PFAS concentrations in treated drinking water would likely remain within the acceptable range. The PFBA concentrations in the treated drinking water reached 1202 ng/L, *exceeding both the sum of 20 PFAS and total PFAS limits* established by the EU. Similarly, PFBA concentrations in raw water exceeded the regulatory thresholds for both categories. While short-chain PFAS is less bioaccumulative, this does not necessarily indicate that they have less potential toxicity than long-chain PFAS (Gomis et al., 2018). Exposure to PFAS has been associated with various adverse health effects, and each PFAS compound may exhibit different bioaccumulation characteristics and toxicological impacts.

In this study, PFOS was detected in both raw water and treated drinking water, with the concentrations in raw water exceeding the regulatory threshold. PFOS is one of the most extensively studied PFAS compounds and has been included in various international regulations related to use restrictions, drinking water standards, and safe exposure limits in humans. PFOS is known for its high bioaccumulative potential. PFOS preferentially binds to proteins in the human body and can accumulate in the liver, blood, muscles, and kidneys, and may even be transferred to the fetus during pregnancy (Beesoon & Martin, 2015; Blake & Fenton, 2020; Dietz et al., 2008). Once accumulated, PFOS is eliminated very slowly, with an estimated half-life in humans ranging from 3 to 5 years (Li et al., 2018). PFOS exposure has been associated with adverse effects on the nervous, immune, reproductive, hepatic, metabolic, and developmental systems. In addition, PFOS has been linked to elevated

cholesterol levels, hypertension, thyroid hormone disruption, and increased risks of certain cancers (Dong et al., 2019; Suman & Kwak, 2025; Xiao et al., 2023a). Owing to its strong bioaccumulative properties and broad range of adverse health effects, PFOS is considered one of the PFAS compounds posing the greatest risk to human health.

PFBA was the dominant PFAS compound detected in raw water and treated drinking water samples. The bioaccumulation potential of PFBA in the human body remains under debate. Pérez et al. (2013) reported relatively high PFBA accumulation in the kidneys and lungs; however, Abraham et al. (2021) re-evaluated this finding and suggested that PFBA accumulates only at relatively low levels in these organs. This observation is consistent with the relatively short biological half-life of PFBA in humans, estimated at 4.2 days, indicating relatively rapid elimination from the body (Abraham et al., 2024). Although PFBA has lower bioaccumulative potential than long-chain PFAS compounds, it still exhibits toxicological effects. Previous studies have reported that PFBA may exert hepatotoxic effects and contribute to liver dysfunction in animals, although further epidemiology studies are needed to address the health effects of PFBA (Wang et al., 2024b; Zhang et al., 2025a)

6:2-Fluorotelomer sulfonic acid (6:2 FTS) was the second most abundant PFAS compound detected in both raw water and treated drinking water from the X DWTP. Compared with long-chain PFAS compounds, 6:2 FTS exhibits relatively low bioaccumulative potential. Although this compound may accumulate in blood and liver tissues; however, approximately 65% can be rapidly excreted through urine within 24 h (Sheng et al., 2017; Wen et al., 2024). The biological half-life of 6:2 FTS in humans is relatively short, estimated at 4.1 days (Abraham et al., 2024). The reported health effects associated with 6:2 FTS exposure include liver damage and inflammatory responses (Sheng et al., 2017). Despite its relatively low bioaccumulative potential, 6:2 FTS is considered an important PFAS precursor compound because it can be transformed into other PFAS compounds in the environment and biota. (Zhao et al., 2021) demonstrated that 6:2 FTS can undergo enzymatic transformation into trifluoroacetic acid (TFA), perfluoropropionic acid (PFPrA), PFBA, PFPeA, and PFHxA in soil and organisms (earthworms), some of which may exhibit greater bioaccumulative properties.

PFDA and PFBS were also detected at relatively low concentrations in both raw water and treated drinking water. PFDA is a long-chain PFAS compound with bioaccumulative properties due to its strong affinity for blood proteins, resulting in slow elimination from the human body and an estimated half-life of approximately 2.4 years (Abraham et al., 2024; D'eon et al., 2010). Although studies on PFDA remain limited compared to PFOS, previous research has shown that PFDA may induce DNA damage, inflammation, lipid and amino acid metabolism disruption, reduced vaccine response, liver toxicity, and metabolic disorders (Cui et al., 2024; Li et al., 2022; Qin et al., 2023; Sun et al., 2025).

PFBS is a short-chain PFAS compound that has a lower bioaccumulative potential than long-chain PFAS compounds. Nevertheless, PFBS may still exhibit significant bioaccumulation potential (Mellouk et al., 2025).. PFBS has hydrophobic characteristics, can accumulate in the liver, and has been associated with hepatotoxic effects (Feng et al., 2024; Sun et al., 2022). Other reported health effects include reproductive and pregnancy-related disorders, neurotoxicity, and cardiotoxicity (Currie et al., 2024; Gong et al., 2022; Mellouk et al., 2025). However, PFBS has a relatively shorter biological half-life in humans, which is estimated to be approximately 51 days (Abraham et al., 2024). Despite its shorter duration, the potential health risks associated with PFBS exposure should not be disregarded.

Overall, the findings of this study demonstrate that PFAS contamination in river surface water may pose not only environmental but also human health risks. Differences in the characteristics of individual PFAS compounds, including their bioaccumulative properties, toxicity, and removal behavior during water treatment, indicate that a comprehensive and integrated approach is required for PFAS management. Therefore, strategic approaches focusing on source reduction, environmental monitoring, and public health protection are necessary to mitigate the environmental and health impacts of PFAS contamination.

3.3 Recommendations for PFAS contamination mitigation strategies in Indonesia

This study identified the presence of PFAS in both raw water and treated drinking water from the X DWTP, indicating the potential risks to public health. However, PFAS regulations and mitigation strategies addressing PFAS contamination and its associated environmental and health impacts are lacking in Indonesia. In contrast, international organizations and several countries have initiated various measures to control PFAS contamination and reduce human exposure risks. These efforts include restricting PFAS use in industrial sectors to minimize contamination at the source, as well as establishing PFAS limits in drinking water to protect public health.

Several countries have implemented restrictions on the use of PFAS in industrial sectors, particularly PFOS and PFOA, as part of their environmental and health risk mitigation strategies. Through the Stockholm Convention, the United Nations Environment program listed PFOS (2009) and PFOA (2019) as Persistent Organic Pollutants (POPs), resulting in restrictions on their production and use (United Nations Environment Programme (UNEP), 2009, 2019). The United States phased out PFOS and PFOA production through voluntary programs facilitated by the US EPA in 2002 and 2015, respectively, while also restricting their industrial applications (US EPA, 2017). Similarly, the European Union implemented stricter controls under Regulation (EU) 2019/1021, which broadly prohibits the use of PFOA and limits the use of PFOS to essential uses under very low contamination thresholds (European Parliament & Council, 2019). Australia has also classified PFOS and PFOA as prohibited chemicals under the Industrial Chemicals Environmental Management (Register) Act 2021 (Australian Government, 2025). In Asia, countries such as Japan and South Korea have also established regulations restricting PFOS and related compounds (Organisation for Economic Co-operation and Development (OECD), 2015). Previous studies have shown that restrictions on the use of PFAS in the industrial sector can effectively reduce PFAS exposure in humans (Calafat et al., 2007).

Mitigation efforts at the exposure stage can also be implemented by establishing of PFAS limits in drinking water. The US EPA and the European Union have established regulatory thresholds for PFAS in drinking water (European Union, 2020; US EPA, 2024). In addition, Australia has set drinking water guideline values for PFOS (8 ng/L), PFOA (200 ng/L), PFHxS (30 ng/L), and PFBS (1000 ng/L) (National Health and Medical Research Council (NHMRC), 2011). Implementing such regulations requires appropriate treatment technologies capable of effectively removing PFAS from drinking water. One potential approach is the application of *Best Available Techniques* (BAT), which refers to the most effective and practical technologies for the removal of PFAS. The US EPA has identified several technologies with high effectiveness for PFAS treatment in drinking water, including ion exchange resin (IEX), high-pressure membrane systems such as reverse osmosis (RO), and granular activated carbon (GAC) (US EPA, 2018). However, to ensure sustainable and practical application, the selection of BAT should consider not only PFAS removal efficiency but also economic feasibility and implementation costs.

In the Indonesian context, PFAS research and mitigation efforts remain limited. Baseline data on PFAS contamination in raw water sources, including river surface water and potentially contaminated groundwater, are urgently needed. In Indonesia, environmental and drinking water monitoring programs are also essential as an initial step toward developing PFAS-related policies. In many countries, mitigation strategies initially focused on restricting PFOS and PFOA because they are among the most extensively studied PFAS, are widely distributed in the environment, and are associated with significant health risks. In this study, PFOS and PFOA were detected in raw water, indicating their persistence in Jakarta's aquatic environment. Therefore, Indonesia could gradually implement restrictions on the use of PFAS in industrial sectors, beginning with PFOS and PFOA, which have already been listed as POPs under the Stockholm Convention. Nevertheless, such restrictions should be accompanied by recommendations for the use of appropriate alternative substances. The United Nations Environment Programme (UNEP) published guidance on potential alternatives to PFOS and PFOA, including fluorinated and non-

fluorinated substitutes (United Nations Environment Programme (UNEP), 2024). These recommendations could serve as a reference for developing practical substitution strategies tailored to industrial sectors in Indonesia. Additional PFAS compounds may also be considered for restriction based on environmental monitoring data and further scientific studies.

In addition to source-control strategies, mitigation efforts aimed at reducing direct public exposureare also necessary. Similar to other countries, Indonesia could establish PFAS limits in drinking water as part of public health protection measures. As an initial step, regulatory efforts may prioritize PFAS compounds, such as PFOS and PFOA, with high bioaccumulative potential and significant health risks. In this study, PFOS was detected in both raw water and treated drinking water, with concentrations in raw water exceeding the US EPA drinking water standard. This finding is important given the strong bioaccumulative properties of PFOS in the human body. Although PFOA was detected only at relatively low concentrations in raw water, its high bioaccumulative potential may still contribute to long-term exposure risks. Indonesia may consider regulating additional PFAS compounds in drinking water in subsequent stages based on their occurrence in raw water sources and their potential health impacts.

In addition to establishing PFAS limits in drinking water, the implementation of appropriate treatment technologies for PFAS removal should support mitigation efforts. In this study, the X DWTP applied reverse osmosis (RO), which was effective in removing long-chain PFAS compounds with high bioaccumulative potential and significant health risks. However, in the context of developing countries such as Indonesia, technology selection should also consider implementation costs and operational feasibility. Although RO is considered one of the most effective technologies for PFAS removal, it requires relatively high operational and maintenance costs (Cordner et al., 2021). The US EPA has recommended several technologies for the removal of PFAS from water sources, and Indonesia may adapt and select treatment technologies that are both effective and applicable under local technical and economic conditions.

Overall, mitigating the environmental and health impacts of PFAS requires a comprehensive approach ranging from source reduction to public health protection. Indonesia may adapt international practices through policies restricting the use of PFAS, establishing drinking water standards, and implementing effective treatment technologies. Strengthening PFAS mitigation efforts will require further development in research, regulatory frameworks, and technological readiness. Therefore, mitigation strategies should be implemented gradually, adaptively, and based on scientific evidence to ensure effective PFAS management while considering Indonesia's technical and economic conditions.

4. Conclusions

This study identified PFAS contamination in raw water, treated drinking water, and reverse osmosis (RO) reject water from the X DWTP, Jakarta. Of the 19 PFAS compounds analyzed, nine were detected, namely, PFBA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFBS, PFOS, and 6:2 FTS. PFBA was the dominant compound, with the highest concentrations in both raw water and treated drinking water. The results demonstrated that the RO unit effectively removed long-chain PFAS compounds, such as PFHpA, PFOA, PFNA, and PFOS, but less effectively removed short-chain PFAS compounds, including PFBA, PFBS, and 6:2 FTS. These findings indicate that although RO treatment can reduce exposure to highly bioaccumulative PFAS compounds, certain short-chain PFAS may still pass through the treatment process and remain detectable in treated drinking water.

Comparison with international drinking water standards showed that PFOS and PFOA concentrations in treated drinking water remained below the US EPA regulatory limits. However, both the *total PFAS* and the *sum of 20 PFAS* exceeded the European Union regulatory thresholds due to the extremely high PFBA concentrations detected in the samples. In raw water, the PFOS concentrations exceeded the US EPA standard. These

findings highlight the importance of effective treatment technologies such as RO for the removal of PFAS from drinking water systems. The occurrence of PFAS in both raw water and treated drinking water may represent a potential human exposure pathway associated with adverse health effects. PFOS and PFOA are particularly important due to their high bioaccumulative potential and significant health impacts. Therefore, mitigation efforts targeting both contamination sources and exposure pathways are necessary to protect the environmental and public health.

Overall, this study demonstrates that PFAS management in Indonesia requires a comprehensive approach involving source reduction, environmental monitoring, and public health protection. This study also provides baseline data on PFAS contamination in Indonesia's surface water-derived drinking water systems, which may support future research, environmental monitoring programs, and the development of PFAS mitigation strategies and regulatory policies.

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Conflicts of Interest
The authors declare no conflict of interest.

Declaration of Generative AI Use
During the preparation of this work, the authors used ChatGPT to assist in improving grammar, clarity, and academic tone of the manuscript. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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