PFAS IN DRINKING WATER: RISK FACTOR FOR HUMAN LIFE, MODERN SOURCES OF POLLUTION, METHODS OF CONTROL AND APPROACHES TO WATER PURIFICATION (REVIEW)

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The current state of aquatic micropollutant contamination is reviewed using polyfluoroalkyl substances (PFAS), which are widely used in industry and are components of consumer products such as cosmetics, fire-fighting foams, household goods, clothing, pesticides, and food packaging. Due to their widespread use and persistence in the environment, PFAS have been detected in rivers and coastal zones, bottom sediments, soils, landfill leachates, and groundwater. It has been found that, due to their heat-resistant properties, PFAS are used as binders in polymer explosives and in various ammunition components. Toxic contamination from ammunition over time may pose a greater danger to the population than the acute detonation of ammunition. Types of per- and polyfluorinated alkyl substances are reviewed. It was found that the most common forms are long-chain perfluorinated PFAS substances, which exhibit carcinogenic, reproductive and immunotoxic properties, are bioaccumulative and can cause liver and kidney toxicity, reproductive and developmental toxicity, endocrine disruption, obesity, type 2 diabetes and various types of cancer. The main methods for the determination of trace amounts of per- and polyfluorinated alkyl compounds are described, including gas or liquid chromatography, tandem mass spectrometry, which are expensive and require complex sample preparation. Currently, solid-phase extraction is preferred for the concentration of micropollutants, which allows expanding the limits of their detection when using gas chromatography and mass spectrometry. A package of tandem chromatography-mass spectrometry methods is recommended for the analysis of PFAS in drinking water. Control methods and approaches to the purification of drinking water sources are reviewed. Electrochemical, sonochemical, advanced oxidation methods, as well as new hybrid methods including the use of nanoadsorbents of natural origin are effective for the removal of short-chain PFAS in laboratory conditions, but have limitations in field application. One of the promising methods for water purification in field conditions is photocatalysis in combination with membrane filtration or electrochemical oxidation.

Keywords: *membrane filtration, methods of determination, micropollutants, polyfluoroalkyl substances (PFAS), toxicity, water purification*

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1. Introduction

Introduction provides information on the relevance, purpose and objectives of the study.

In recent years per- and polyfluoroalkyl substances (PFAS) have been attracting increasing scientific and political attention worldwide. According to the revised definition of the Organization for Economic Co-operation and Development (OECD), per- and polyfluoroalkyl substances (PFAS) include any chemical substance containing at least one saturated -CF_2- or -CF_3 moiety (Schymanski et al., 2023). Per- and polyfluoroalkyl substances (PFAS) are known as a group of "forever chemicals" that can persist in the environment for long periods, bioaccumulate in living organisms, and are highly mobile in water and soil.

Per- and polyfluoroalkyl substances are synthetic compounds used in a wide range of industrial and consumer products due to their unique physicochemical properties (Buck et al., 2011), the production of which began in the late 1940s. PFAS have a strong covalent bond between C-F. Fluorine, due to its electronegativity and small size, is responsible for properties such as high acidity, water repellency and oleophobicity, which make the perfluoroalkyl ($C_nF_{2n}^{+1}-$) fraction preferable for many applications than its hydrocarbon counterparts. Today, PFAS, due to their oil-repellent properties, low surface tension and high heat resistance, are used in a wide range of industrial (in particular, mining) and consumer products, such as cosmetics, fire-fighting foams, household goods, clothing, pesticides, food packaging materials (Buck et al., 2011; Xu et al., 2025). They are widely used in the production of semiconductors (photolithography method), are used as photoacid generators (PAGs), in anti-reflective coatings, and are used in anti-foaming surface treatment of textiles and leather (firefighter clothing), brickwork, paper and cardboard (leveling agents in paints) (Yuexin et al., 2025). Due to their heat-resistant chemical properties, PFAS are used as binders in polymer-bonded explosives (PBXs) and various ammunition components. Toxic contamination from munitions over time may pose a greater risk to a larger population than the acute detonation of munitions. (Koban & Pfluger, 2022; Hryhorczuk & Levy, 2024).

During the implementation of the HBM4EU initiative in 2017-2021, experts identified a list of 18 substances that require careful monitoring due to their possible impact on human health: acrylamide, the aniline family, aprotic solvents, arsenic, benzophenones, bisphenols, cadmium (Cd), chromium VI (Cr VI), flame retardants, lead (Pd), mercury (Hg), mycotoxins, per-/polyfluorinated compounds (PFAS), volatile pesticides, phthalates and Hexamoll®DINCH, polycyclic aromatic hydrocarbons (PAHs), plastics that are subject to mandatory environmental monitoring (Haverinen, 2021; Ganzleben, 2017; HBM4EU, 2021; Schoeters & Lange, 2021; Scott & Gunderson, 2021).

In addition, the European Food Safety Authority (EFSA) CONTAM Panel established a tolerable weekly intake (TWI) for perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA), perfluorohexanesulfonic acid (PFHxS) and perfluorooctanesulfonic acid (PFOS) at 4.4 ng/kg body weight (bw) per week (EFSA, 2020).

The most common and well-studied forms of PFAS have been identified as PFOA and PFOS. PFOA and PFOS are long-chain perfluorinated compounds that have been shown to have carcinogenic, reproductive, and

immunotoxic properties, as well as the ability to affect the thyroid gland and lipid metabolism (Barry & Winquist, 2013; Kim & Moon, 2018; Liu & Zhang, 2020). Several other long-chain PFAS have also been identified as highly persistent, bioaccumulative, and toxic, with elimination times ranging from years to decades in humans (EFSA, 2020).

Additionally, there is also concern about short-chain PFAS, which are considered less bioaccumulative but still remain persistent and are found in drinking water and food, including vegetables (Schoeters & Lange, 2021; Yuexin et al., 2025).

Due to their widespread use, PFAS have entered our environment as new pollutants, so their monitoring is vital both from the standpoint of environmental management and the study and assessment of human exposure risks. Since they are not natural molecules, with rare exceptions such as monofluorinated compounds produced by plants or perfluoroalkylates formed as a result of geophysical processes, they are found in insignificant quantities in the environment, but for all other compounds, their presence in the environment is of exclusively anthropogenic origin (Brunn et al., 2023; Elgarahy et al., 2024; Lewis et al., 2023). The ability of PFAS to accumulate in trace amounts in different environmental compartments is one of the main problems that limits their analysis.

The U.S. Environmental Protection Agency (EPA, USA) has published guideline levels for four of the most common chemicals: perfluorooctanoic acid (PFOA), perfluorooctane sulfonic acid (PFOS), and their short-chain substitutes perfluoro-2-propoxypropanoic acid (GenX) and perfluorobutanesulfonic acid (PFBS), respectively (USEPA, 2024).

To conduct an analytical review of the current state of environmental and aquatic pollution by polyfluoroalkyl substances (PFAS), to show the risks to human health if they enter drinking water, control methods and approaches to purifying drinking water sources.

2. Materials and Methods

The study is based on an analysis of domestic and foreign publications on the current state of environmental pollution by PFAS compounds, analysis of its content in environmental objects and sources of drinking water supply, toxicity of PFAS to humans, implemented regulatory and legal acts in the world, guiding documents of international organizations and those operating in Ukraine.

3. Results and Discussion

An analysis of the number of publications in PubMed on environmental contamination with PFAS and their impact on human health showed a significant increase in scientific works over the past 10 years (Fig.1.).

The number of publications devoted to the study of the content of PFAS in various objects of the environment and the impact on the human body among individual countries of the world is presented in Fig. 2. This issue is most actively studied in Canada, China and the USA, which is probably due to the patent activity of scientists in these countries. The leadership of USA is explained by the active work of EPA experts, the country is a leader in the development of equipment and methodology for determining PFAS in water.

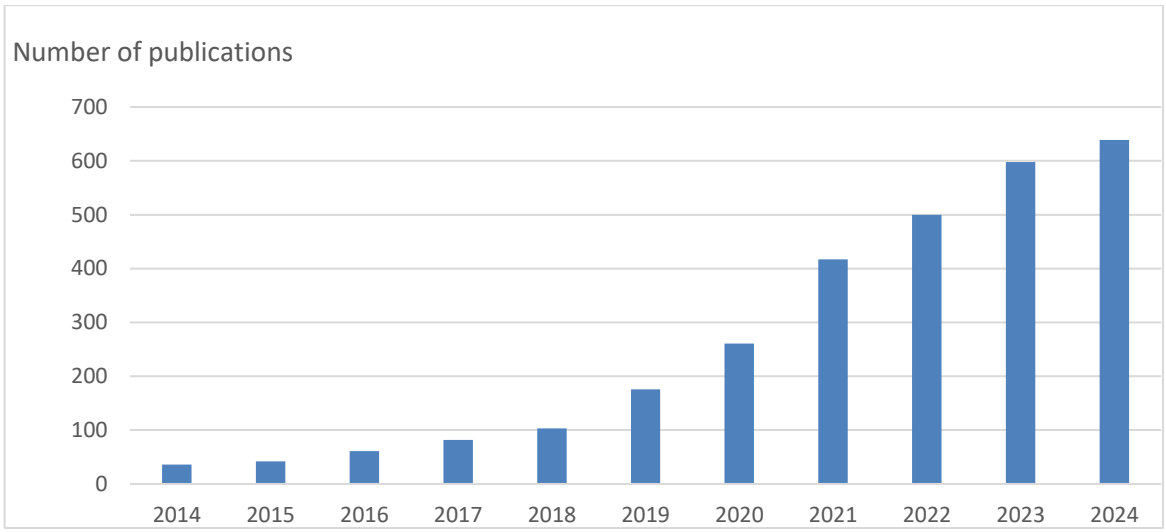

Fig. 1. *Number of publications on PFAS in PubMed*

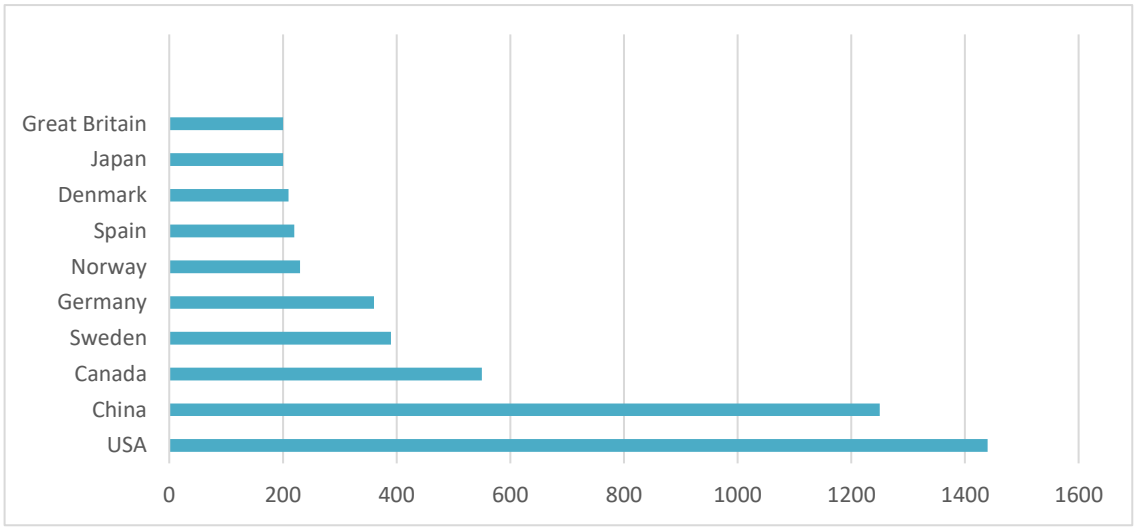

Fig. 2. *Number of publications on PFAS in 10 countries around the world from 2000 to 2020 (Ziyad et al. 2020)*

In recent years, the persistence of PFAS in the environment, their biomagnification in food chains, and their potential accumulation and toxicity have attracted considerable interest, as evidenced by a significant number of publications on this subject. A recent broad review of PFAS levels in food and the human diet has been conducted. Over the past 10 years, the following information has been summarized (Domingo & Nadal, 2019), published in the scientific literature (Scopus and PubMed), on PFAS concentrations in drinking water and the human health risks associated with regular water consumption, when present.

3.1 Monitoring PFAS in waters of different countries

Due to their widespread use and persistence in the environment, PFAS have been detected in rivers and coastal areas (Pan et al., 2018; Yamazaki et al., 2019), bottom sediments (Xiao et al., 2021), soils (Tan et al.,

2014), atmospheric particulate matter (Yu et al., 2020), landfill leachates (Gallen et al., 2016), and groundwater (Li et al., 2020; Lu et al., 2018).

Infiltration from industrial effluents, soil exposed to aqueous film-forming foam (AFFF), and the application of biosolids and compost containing PFAS can lead to groundwater contamination (Barzen-Hanson et al., 2017; Gwynn, 2022). However, compared to studies in other environmental settings, knowledge of PFAS levels in groundwater is limited. Reports of PFAS in groundwater have largely focused on regions exposed to AFFF, industrial and non-industrial areas, and landfills (Barzen-Hanson et al., 2017; Baduel et al., 2017; Dauchy et al., 2019; Harrad et al., 2020; Lu et al., 2018; Nickerson et al., 2021; Wei et al., 2018; Xu et al., 2021). PFAS concentrations in such studies ranged from 300 ng/L to 8,300 ng/L near a firefighter training site in France (Dauchy et al., 2019), 4.8-614.6 ng/L near a fluorochemical industrial park in China (Lu et al., 2018), and 17.3 ng/L -163 ng/L near a landfill in China (Xu et al., 2021).

Additionally, total PFAS concentrations in groundwater of the Maozhou River Basin and Yangtze River Delta in China were much higher than in surface waters (Li et al., 2020; Lu et al., 2018; Jie & Guyu, 2022).

In turn, in bottled water, the highest levels were found in a water sample from a French manufacturer, where the sum of PFAS was 116 ng/L (Schwanz et al., 2016). However, in another short study conducted in Belgium (Cappelli & Ait, 2024) in 47 samples of tap water collected in different Flemish provinces and 16 samples of bottled water purchased in Flanders. Of the 7 targeted PFAS, 4 (PFBA, PFBS, PFPrS and PFEtS) were detected in concentrations above the LOQ in tap water.

The most common compounds and those with the highest concentrations were perfluoroheptanoic acid (PFHpA) with an average frequency across the three countries of 51.3%, perfluorobutanesulfonic acid (PFBS) (27.2%) and perfluorooctanoic acid (PFOA) (23.0%). Considering that bottled water represents approximately 38% of total water consumption, the total exposure to PFAS through drinking water consumption for an adult was 54.8 ng/(person·day) in Spain, 58.0 ng/(person·day) in France and 75.6 ng/(person·day) in Brazil. However, assuming that the water content of other beverages has at least the same levels of contamination as bottled drinking water, these values were increased for an adult to 72.2 ng/(person·day) in Spain, 91.4 ng/(person·day) in France and 121.0 ng//(person·day) in Brazil (Thiago et al., 2016).

In a monitoring campaign (Jie et al., 2022) in the North China Plain, 43 PFASs from two different aquifers were investigated. It was found that the total concentrations of PFASs (∑43PFASs) ranged from 0.22 ng/L to 3776.76 ng/L, with no spatial or compositional differences. Moreover, perfluorooctanoic acid (PFOA) and perfluoroheptanesulfonate (PFHS) were the dominant contaminants with mean concentrations of 51 ng/L and 177.33 ng/L, respectively. It was found that the total content of PFASs (∑43PFASs) decreased with well depth due to adsorption of PFASs on aquifer materials. Water temperature, total organic carbon, dissolved oxygen, and total phosphorus were correlated with PFAS concentrations.

The study found PFAS in wastewater treatment plant (WTP), surface water, and

commercially available bottled and tap water in African countries. PFAS concentrations in the drinking water sources studied ranged within the limits of quantification up to 778 ng/L. Sources of PFAS in African water systems are related to uncontrolled imports of PFAS-containing products, wastewater from WWTPs, and improper disposal of PFAS-containing materials. Most water treatment plants currently in operation in African countries cannot effectively remove PFAS during treatment.

Most water treatment facilities currently implemented in African countries cannot effectively remove PFAS during treatment (Adewuyi & Qilin, 2024).

Principal component analysis showed that the main sources of PFAS in groundwater were untreated industrial discharges, untreated domestic wastewater, food packaging, aqueous film-forming foams and surface runoff from industries in a nearby city. As a result of monitoring, a site was found where the PFOA content was 70 ng/L, which was several orders of magnitude higher than the value recommended by experts from the US Environmental Protection Agency (Jie et al., 2022). In contrast to factors affecting surface water, several studies have shown that geochemical factors (e.g., pH, salinity, and dissolved organic matter) can affect the sorption of PFAS in groundwater, and the concentration of cations (i.e., Ca^{2+}, Mg^{2+}) can also affect the adsorption of PFAS by binding to the anionic head groups of PFAS (Wu et al., 2020). Furthermore, groundwater typically contains low levels of dissolved solids, which may affect the degradation of PFAS precursors during aerobic biotransformation (Harding-Marjanovic et al., 2015). Therefore, knowledge about the factors influencing the distribution of PFAS in groundwater from contaminated sites remains limited.

3.2. The effect of PFAS on humans

In recent years, due to their tendency to bioaccumulate and their harmful effects on both the environment and living organisms, including humans, a large group of PFASs has been a source of great concern (Lenka et al., 2021; Ziyad et al., 2021; Peritore et al., 2023; Rosato et al., 2024). Due to the extreme persistence of these substances in the environment, humans and all other life forms are increasingly exposed to these substances (Fig. 3.). Despite their widespread use, the toxicity and bioaccumulation potential of PFASs remain poorly understood (Bellia & Bilott, 2023). Moreover, for most of them, experimental data and testing standards are lacking.

The U.S. Environmental Protection Agency has released drinking water guideline levels for four of the most common chemicals: perfluorooctanoic acid (PFOA), perfluorooctane sulfonic acid (PFOS), and their short-chain substitutes perfluoro-2-propoxypropanoic acid (GenX) and perfluorobutanesulfonic acid (PFBS), respectively (USEPA, 2022).

Rapidly developing countries such as India need a deep understanding of PFAS contamination levels and potential risks to the environment and human health, especially given the very limited research on PFAS in India (Koulini & Nambi, 2024). Previously, PFAS were reported in India in human breast milk (total mean PFOS: 46 ng/L) (Kannan et al., 2004), tap water (perfluorohexanesulfonic acid, PFHxS up to 81 ng/L) (Mak et al., 2009), Gangetic river dolphins (PFOS: 27.9 ng/g body weight) (Yeung et al., 2009), surface sediments

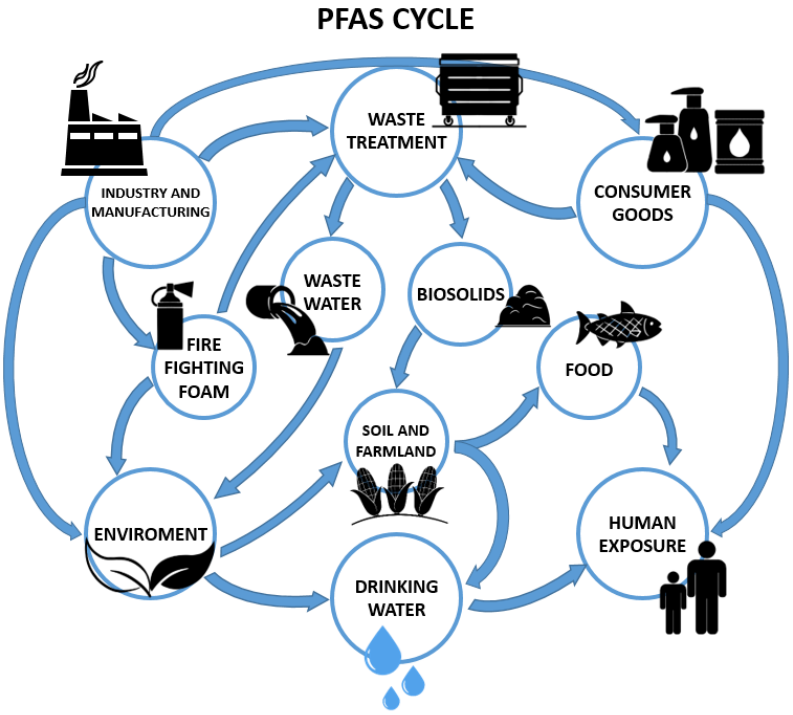

Fig. 3. *Graphical representation of environmental migration and human exposure to PFAS*

(PFOA: <0.5 ng/g - 14.09 ng/g) and surface/groundwater (PFBS: <MQL - 10.2 ng/L) (Sharma et al., 2016). Although little is known about the production and use of PFAS in India (Toxic Links, 2019), recent studies have also reported the presence of PFAS in various environmental media such as human hair, road dust, surface water and groundwater in different regions (Koulini & Nambi, 2024; Ruan et al., 2019; Yamazaki et al., 2023). These studies substantiate the prevalence of PFAS in the Indian environment. However, the distribution status and historical dynamics of PFAS are poorly understood, and there is no regulation of PFAS in India (Yamazaki et al. 2025).

Studies by authors (Mondal et al., 2012; Halldorsson et al., 2012; Geiger et al., 2013; Braun & Chen, 2016; Wen et al., 2020; Averina & Brox, 2021; Santhanam & Ramamurthy, 2024) have established that PFAS, especially long-chain PFAS, are bioaccumulative and can cause liver and kidney toxicity, reproductive and developmental toxicity, endocrine disruption, and various types of cancer. Establishing a link between the interaction of PFAS with proteins and specific adverse outcomes (bioaccumulation and toxicity) can facilitate efficient and accurate ranking of numerous PFAS based on hazard with fewer resources over time. Understanding these relationships provides the basis for predicting toxicity and risk, even if some of the intermediate key events still remain unclear. (Yifeng et al., 2013; Rosen et al., 2022; Yuexin et al., 2025).

A review (Qi & Clark, 2020; Haverinen, 2021) of the epidemiological data on the association between PFAS exposure and the development of obesity, diabetes, and nonalcoholic fatty liver disease found some evidence for such an association. Of the total number of studies (55 people), approximately two-thirds reported a positive association between PFAS and the prevalence of obesity and/or type 1, type 2, or gestational diabetes

(Qi & Clark, 2020; Preston et al., 2020). For children, the evidence appears less convincing, as only the development of dyslipidemia indicated a positive association with PFAS exposure (Rappazzo, 2017; Fragki et al., 2021; Kim et al., 2023), and the role of PFAS in the development of metabolic syndrome is also discussed (Christensen et al., 2019).

One study examined the effects of PFAS on metabolism and found that PFAS was associated with an increased risk of metabolic syndrome, increased waist circumference, increased triglycerides, and decreased HDL when controlling for several PFAS. Although perfluorodecanoic acid (PFDA), PFOA, 2-(N-methyl-PFOSA) acetate (MPA), and perfluoroundecanoic acid (PFUNDAC) were associated with reduced risk of certain persistent organic pollutant (POP) components, the most consistent pattern was seen with PFUNDAC (Christensen et al., 2019). Among overweight and obese participants, PFAS were associated with higher concentrations of apoB and apoC-III, but not total cholesterol or triglycerides (Liu & Zhang, 2020). From a metabolic perspective, PFAS exposure has been linked to metabolic disorders, including obesity, type 2 diabetes mellitus (T2DM), dyslipidemia, and liver toxicity, especially in early childhood (Lucas, 2024).

In studies of vulnerable populations, children have been found to have higher serum concentrations of PFOA compared to adults (Mondal, 2012; Braum et al., 2016; Huang et al., 2019; Peterson et al., 2022; Forthun et al., 2023). In utero exposure to PFOA has been associated with childhood obesity (Halldorsson, 2012; Geiger, 2013; Braun et al., 2016; Kim et al. 2024). Among adolescents, serum concentrations of PFOS, PFNA, PFDA and PFUnDA were positively associated with apolipoprotein B. Concentrations of PFAS, PFHxS, PFOS, and PFOA were positively associated with the risk of arterial hypertension, and concentrations of PFHxS and perfluoroheptanesulfonic acid (PFHpS) were also positively associated with obesity (Averina et al., 2021; Romano et al., 2022). No association was found between PFAS exposure and the development of hypertension in children (Geiger, 2013), however, an association of PFAS accumulation with the development of bronchial asthma in children has been described (Jackson-Browne & Eliot, 2020).

Among pregnant women, gestational diabetes mellitus (GDM) and the impact of PFAS on the development of diabetes mellitus (DM) have so far shown inconsistent and component-specific differences (Santander, et al., 2017; Preston et al., 2020; Xu et al., 2020). In one study, exposure to PFOS, PFOA, PFHxS, PFNA, 2-(N-ethyl-perfluorooctanesulfonamide) acetate, N-ethylperfluorooctanesulfonamido acetate (EtFOSAA), N-methylperfluorooctanesulfon-aminodoacetate (MeFOSAA), perfluorodecanoate, and perfluorooctanesulfonamidoacetate (FOSAA) did not reveal any association between glucose tolerance and PFAS exposure (Preston, E.V.; Rifas-Shiman, S.L., 2020).

Two other studies showed that serum levels of perfluorobutanesulfonate (PFBS) and perfluorododecanoic acid (PFDOA) were significantly higher in the GDM group compared to controls (Xu et al., 2020, Hron et al., 2023), and in another study, PFOS and PFHCs were associated with impaired glucose tolerance or gestational diabetes mellitus (Santander et al., 2017). A possible association between pregnancy-induced hypertension (PIH) and PFOS exposure was found in one

study (Huang et al., 2019), as another study found high levels of PFOS in the placenta, but there was no evidence for hypertensive disorders during pregnancy (Bangma et al., 2020). PFOA have also been linked to increased maternal total cholesterol levels (Santander et al., 2017).

As PFAS have been shown to be associated with a variety of adverse health effects, new substitutes are constantly appearing on the market. For example, 2,3,3,3-tetrafluoro-2-(heptafluoropropoxy)propanoic acid (GenX) was developed to replace the use of PFOA. GenX has shown some evidence of metabolic abnormalities, but to a lesser extent than PFAS (Wen et al., 2020). Another PFOA substitute, chlorinated polyfluorinated esters of sulfonic acids (Cl-PFESA), has been associated with increased prevalence of hypertension and elevated blood cholesterol levels (Fleury et al., 2024). Furthermore, women have been shown to be more susceptible to changes associated with Cl-PFESA (Mi et al., 2020). However, knowledge about the effects of these compounds and their negative impact on health is still limited.

The work (Fragki et al., 2021) reviewed the assessment of the impact of PFAS (mainly PFOS and PFOA) on cholesterol and triglyceride homeostasis. Epidemiological studies (Guo et al., 2022) show a positive association between increased blood total cholesterol and, in some cases, triglycerides with increased PFOS/PFOA levels, but most of them are cross-sectional studies. In vitro studies on liver cells have shown that PFOS/PFOA activate several other nuclear receptors. In addition, data indicate that inhibition of the nuclear receptor HNF4 signaling pathway, as well as disruption of bile acid metabolism and transport, may be important molecular events, which, however, require further investigation.

It should be noted that a number of studies have shown the effect of PFAS on the endocrine system (therefore, they are included in the list of endocrine disruptors). PFAS potentially affect the cognitive development of newborns due to thyroid dysfunction during pregnancy (Rickard, 2023; Gaillard, 2024), an increased risk of gestational diabetes in newborns in China was found in early pregnancy (Xu et al., 2020), the known effect of PFAS on the development of dyslipidemia, hypertension and obesity in adolescents in Norway (Averina et al., 2021). Recent studies have revealed different reproductive toxicity for men and women. Different classes of PFAS affect male reproductive function (reduced sperm), and long-term exposure to PFAS correlates with diseases such as endometriosis in women (Mi et al., 2020; González-Alvarez et al., 2024).

Women, unlike men, exhibit unique pathways of exposure and excretion of PFAS, leading to complex health outcomes. Women's health is largely influenced by hormone-related processes. PFAS have been reported to be associated with various aspects of women's health, including reproductive disorders and pregnancy-related diseases (Santander et al., 2017). Current epidemiological and toxicological evidence has demonstrated that adverse effects of PFAS on female reproductive health are primarily attributed to disruption of the hypothalamic-pituitary-gonadal (HPG) axis and hormonal homeostasis (Bangma et al., 2020). However, these findings do not sufficiently elucidate the complex relationships between PFAS and specific diseases. Additionally, autoimmune disorders, another category that is more prevalent among

women compared to men, require additional research (Sun et al., 2023; Cai et al., 2025).

The US National Health and Nutrition Examination Survey (NHANES) conducted a cohort study of PFAS in serum of children aged 12 years and older (639 participants). Serum concentrations of 14 PFASs, including perfluorooctanesulfonic acid (PFOS), perfluorooctanoic acid (PFOA), perfluorohexanesulfonic acid (PFHxS), and perfluorononanoic acid (PFNA), were quantified in a representative subsample of 639 NHANES 2013-2014 participants aged 3-11 years (Ye et al., 2018). However, in a study conducted in In New Hampshire (UK) in 2014 (Daly et al., 2018) in serum samples of 1578 individuals in >94% of cases perfluorooctane sulfonic acid (PFOS), perfluorooctanoic acid (PFOA) and perfluorohexanesulfonic acid (PFHxS) were detected. The mean serum concentrations of PFOS, PFOA and PFHxS were 8.6 μg/l (95% CI: 8.3-8.9), 3.1 μg/l (95% CI: 3.0-3.2) and 4.1 μg/l (95% CI: 3.9-4.3) respectively, which was higher than the general indicator in the USA.

The detection of PFOS, PFOA, PFHxS, and PFNA in U.S. children at concentrations similar to those reported by NHANES in 2013-2014 in adolescents and adults suggests widespread exposure to these PFAS or their precursors among U.S. children ages 3-11, most of whom were born after the phase-out of PFAS in the United States (since 2002). In July 2024, NIOSH published a Health Hazard Assessment Report that summarized comprehensive biological monitoring results and recommended limits on exposure to PFAS if serum levels exceed the clinical threshold of 20 μg/L. The differences in PFAS concentrations by gender, race/ethnicity, and age, as well as differences in lifestyle, underscore the importance of identifying sources of exposure and studying the effects of PFAS on human health (Ye et al., 2018; Beaucham et al., 2025).

3.3. Methods for analytical control of PFAS contamination of water

The first chromatographic tool used to test for PFAS was ion chromatography (IC). This is a type of liquid chromatography that is sensitive enough for these chemicals, as long as the detection limits are not too low, to detect PFAS in drinking water. With the introduction of solid-phase extraction (SPE), which can concentrate the contaminant before separation by chromatography, the detection limits were lowered when using gas chromatography (GC). However, the detection limits for PFAS were still insufficient. Today, SPE followed by liquid chromatography and mass spectrometry (GC-MS) is the preferred method. This has lowered the detection limits and allowed the detection and analysis of individual PFAS, allowing for the study of their migration in the ecosystem.

In recent years, PFAS detection methods have been introduced in various countries, such as the US EPA, ASTM, DIN, and a number of other standard methods. Their list is constantly expanding, and additional rules for working with them are also being adopted.

Currently available methods for detecting PFAS include gas or liquid chromatography (GC or LC), tandem mass spectrometry (MS/MS), methods (Igarashi et al., 2021), which are expensive, time-consuming, and require sending samples to centralized laboratories for analysis.

The United States Environmental Protection Agency (US EPA) has placed great emphasis on developing sensitive, routine, and reliable assays for the detection of PFAS in a variety of environmental media, with a focus on drinking water. In August 2021, the US

EPA published draft method 1633 for the analysis of 40 PFAS compounds in a variety of environmental media. As of August 2023, four draft methods have been published for the determination of PFAS in a variety of natural water types, with a multi-laboratory validation study completed for the analysis of water samples. (Report EPA, 2024, 2024a).

The U.S. Environmental Protection Agency (US EPA) has standardized two methods for the analysis of per- and polyfluoroalkyl substances (PFAS) in drinking water: EPA Method 537.1 and EPA Method 533, covering a total of 29 PFAS. These methods were used as references to develop a validated LC/MS/MS Method Package for the Analysis of PFAS in Drinking Water. This method package (EPA 533 and 537.1) contains ready-to-use analytical conditions, example analytical procedures for the methods, and various other information, such as sample preparation precautions and analysis conditions. These documents can be used to analyze 52 PFAS compounds in drinking water.

The work (Jurikova et al., 2022) presents a solid-phase extraction method for the determination of 22 PFAS in water using 100 ml of sample. Instrumental analysis using ultra-high-performance liquid chromatography combined with tandem mass spectrometry allowed to achieve low limits of quantification (0.025-0.25 ng/l). The validated method (recovery 70-120% and repeatability ≤ 20% at the tested concentrations (0.05 ng/l, 0.1 ng/l and 0.5 ng/l)) was applied to 67 tap water samples and 31 bottled water samples collected in the Czech Republic. The most common compounds detected in the samples tested were perfluoronoic acid (88% positive; 0.034 ng/L -13.3 ng/L) and perfluoroheptanoic acid (23% positive; 0.035-0.106 ng/L), respectively. Total PFAS levels in positive samples ranged from 0.029 ng/L to 300 ng/L (99% positive, median 2.34 ng/L) in tap water and from 0.033 ng/L to 4.48 ng/L (32% positive, median 0.097 ng/L) in bottled water samples. Modern fluoroalkyl esters - dodecafluoro-3H-4,8-dioxanoneanoate and 11-chloroeicosafluoro-3-oxaundecane-1-sulfonate - have occasionally been detected in tap water.

In another study by American scientists (Chow et al., 2021), Solid-phase extraction-liquid chromatography-tandem mass spectrometry (SPE-LC-MS/MS) was used to determine PFAS in bottled waters. Fifteen of the 32 analytes measured were detected, consisting mainly of C_3-C_{10} perfluorocarboxylic acids (PFCAs) and C_3-C_6 and C_8 perfluorosulfonic acids (PFSAs). PFAS were detected above the detection limits of the method in 39/101 tested products. The detected concentrations of Σ32PFAS were 0.17 ng/L - 18.87 ng/L with a median of 0.98 ng/L; 97% of the samples were below 5 ng/L. PFCA (83%) and short-chain perfluoroalkyl acids (PFAA) containing 5 or fewer CF2 groups (67%) were more abundant by mass than PFAS and long-chain PFAA, respectively. Ultrashort-chain PFPrA, first measured in bottled water, accounted for the largest individual fraction of PFAS mass detected (42%) and was found almost exclusively in products labeled as spring water. Purified water contained significantly less PFAS than spring water, which is explained by the use of reverse osmosis (RO) in most purified waters (25/35) compared to spring waters (1/45).

Ultra-performance liquid chromatography (UPLC) coupled with Orbitrap mass spectrometry (Orbitrap-MS) using an electrospray ionization (ESI) interface was used to quantify these PFAS in wastewater

and natural waters (Miserli et al., 2023). The most abundant PFAS in all water types in Greece (Ionian Sea, Pamvotis Island and hospital wastewater after treatment) were perfluorooctane sulfonamide (PFOS) and perfluoro-n-octanoic acid (PFOA) with concentrations up to 21 ng/L (secondary wastewater) and 160 ng/L (hospital wastewater), respectively. This study showed that long-chain PFAS (C_8–C_{13}) constitute up to ~38.5% of the total PFAS concentration in secondary wastewater of municipal and hospital wastewater.

U.S. EPA Method 1633 is a laboratory-validated test method for 40 PFAS compounds, including linear and branched isomers, in wastewater, surface water, groundwater, soil, biochemical solids, sediment, landfill leachate, and fish tissue. In addition to some new classes of PFAS, all analytes listed in EPA Drinking Water Methods 533 and 537.1 are included. This method is a standardized and reliable method for monitoring PFAS in non-potable water and soils.

Analysis of sample extracts is performed by LC/MS/MS in multiple reaction monitoring (MRM) mode after solid phase extraction using weak anion exchange and carbon purification. Agilent sample preparation tools, consumables, columns, and robust triple quadrupole (TQ) LC/MS instruments offer end-to-end workflow solutions to confidently meet EPA 1633 performance requirements while providing maximum reliability and easy maintenance.

Table 1. *Methods for determining PFAS in water have been implemented in the USA and Europe (for LC-MS/MS)*

Region	Method name	Water type	PFAS amount
USA	EPA 537&537.1	Drinking water	25
	EPA 533	Surface and groundwater	18
	EPA SW 846 method 8327	Surface, ground- and wastewater	29
	ASTM D&8421	Municipal water, industrial wastewater, groundwater and surface water, filtrate	52
	EPA1633 ASTM D8535	Soils, sediments, sludge, solids	24
Europe	ISO 25101:2009	Drinking, groundwater and surface water	2
	ISO 21675:2019	Drinking, natural and wastewater waters	30

3.4. Approaches to cleaning drinking water sources from PFAS

In connection with the establishment of regulations to limit the level of per- and polyfluoroalkyl substances (PFAS) in drinking water and wastewater, effective treatment technologies are needed to remove or destroy PFAS in contaminated liquid matrices (Pinkard et al., 2023).

PFAS treatment strategies are still in their infancy, and researchers are exploring innovative and sustainable methods for cleaning up contaminated environments. Promising technologies such as adsorption, biodegradation, and electrochemical oxidation

have demonstrated the potential to remove PFAS from contaminated sites, but the search for more effective and sustainable solutions continues (Chen et al., 2007; Giri et al., 2012; Gagliano et al., 2020; McIntyre et al., 2022; Hao et al., 2022; Hao et al., 2023; Burlakova & Mitchenko, 2024). As we move forward, it is necessary to prioritize sustainable solutions that minimize the adverse impacts of these substances on human health and the environment (Elgarahy et al., 2024; Yang et al., 2024, Cao et al., 2025).

The study of approaches to remove poly- and perfluoroalkyl substances (PFAS) from the environment is rapidly increasing due to concerns about environmental contamination and the associated negative toxicological effects on wildlife and human health risks (Wanninayake, 2021). Although PFAS are very difficult to remove by conventional water treatment processes (Jin et al., 2021). For example, chlorination was not effective in removing PFAS, although the total concentration in treated water was high, ranging from 86 ng/L to 169 ng/L, it did not exceed the currently available regulatory values (Bellia et al., 2023).

However, some effective methods exist. These methods are associated with extremely high costs due to high energy consumption, as well as high capital and operating costs. Most methods for separating and destroying PFAS today have their limitations in the field, while biological approaches to PFAS removal are extremely limited and are currently in the early stages of development.

Electrochemical, sonochemical, advanced oxidation methods and plasma, as well as new hybrid methods are considered to be effective approaches for PFAS removal and have shown their effectiveness in removing short-chain PFAS under laboratory conditions.

Many military installations and airports have fire training ponds (FTPs) where PFAS-containing firefighting foam is discharged during training exercises (Pinkard et al., 2023). Disposal of water from these ponds is expensive and difficult due to the high PFAS content. Hydrothermal alkaline treatment (HALT) has been shown to destroy a wide range of PFAS compounds. Treatment with a 5 M NaOH solution and 1.6 min of continuous treatment results in >99% total destruction of PFAS, and a 10 min treatment time results in >99% destruction of each of the PFAS species measured. Treatment of water with NaOH solutions of varying concentrations has little effect on the destruction of the measured perfluorosulfonic acids, while all measured perfluorocarboxylic acids and fluorotelomer sulfonates are reduced to levels below the detection limit of the method. Continuous HALT treatment with sufficient NaOH loading destroys the parent PFAS compounds significantly faster than batch HALT treatment, which is a positive indicator for scaling up HALT technology for practical application in environmental remediation efforts.

The review article by the authors (Verma et al., 2021) summarizes the degradation technologies and provides in-depth knowledge on photodegradation, electrochemical degradation, chemical oxidation and the mechanism of reductive mineralization. New non-degradable technologies are also discussed in detail, including nanoadsorbents (Song et al., 2011; Liu et al., 2021), natural and surface-modified clay minerals/zeolites (Yan et al., 2021), calixarene-based polymers, as well as molecularly imprinted polymers and adsorbents derived from biomaterials (McCleaf et al., 2017). Of these new approaches, photocatalysis combined with

membrane filtration or electrochemical oxidation shows promising results in the removal of PFAS in natural waters (Saawarn et al., 2022; Liu et al., 2022; Hori et al., 2022; Verma et al., 2024).

The "forever" aspect of PFAS makes their removal from the environment particularly challenging. However, scientists are now exploring a promising microbial approach that could help reduce contamination (Berhanu et al., 2023). A recent study published in the journal Science of the Total Environment found that Labrys portucalensis F11, a strain of bacteria found at a contaminated industrial site in Portugal, can break down up to 90% of PFAS.

According to Diana Aga, a co-author of the study from the University at Buffalo (Yang et al., 2024), most microbes cannot break down PFOS because of their exceptionally strong chemical bonds, but the microbe F11 has the unusual ability to "split fluorine and eat carbon". Although solutions like F11 are still in the early stages of research, they could offer humanity a potentially sustainable way to reduce the harmful effects of these persistent chemicals. Given the global prevalence of PFAS contamination, microbial control of them could become an important tool in the fight against pollution. If scientists can scale up the use of bacteria that consume PFAS, the "forever" aspect of these chemicals could one day be a thing of the past

4. Conclusions

The results of the research of scientists from around the world present the first evidence of PFAS contamination of the environment and shed light on this global problem of the world from various aspects of their action. Ultimately, the inclusion of the experience of existing research conducted by scientists in the USA, Europe and countries of Asia strengthens the momentum for global joint efforts in solving problems related to environmental pollution with PFAS.

PFAS contamination of air, water and soil is a complex problem today that requires immediate attention and action. The health problems associated with PFAS exposure are widespread and affect both the population and the environment. Governments, industry and the public must work together to implement strict regulations on the control, regulation and management of PFAS, invest in research and monitoring programs, and promote sustainable alternatives to products containing PFAS. Only by working together can we effectively combat the hidden threat posed by PFAS and protect human health and preserve the fragile balance of ecosystems.

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ПФАС У ПИТНІЙ ВОДІ: ФАКТОР РИЗИКУ ДЛЯ ЗДОРОВ'Я ЛЮДИНИ, СУЧАСНІ ДЖЕРЕЛА ЗАБРУДНЕННЯ, МЕТОДИ КОНТРОЛЮ ТА ПІДХОДИ ДО ОЧИЩЕНННЯ ВОДИ (ОГЛЯД ЛІТЕРАТУРИ)

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Здійснено огляд сучасного стану забруднення водного середовища мікрозабруднювачами на прикладі поліфторалкільних сполук (ПФАС), які широко використовуються в промисловості та є компонентами споживчих товарів, таких як косметика, протипожежні піни, побутові товари, одяг, пестициди, пакувальні матеріали для харчових продуктів. Через широке застосування та стійкість у навколишньому середовищі ПФАС були виявлені в річках та прибережній зонах, донних відкладеннях, ґрунтах, фільтратах сміттєзвалищ та ґрунтових водах. Виявлено, що завдяки своїм термостійким властивостям ПФАСи використовуються як зв'язуючі речовини в полімерних вибухових речовинах та в різних компонентах боєприпасів. Токсичне забруднення від боєприпасів з часом може становити більшу небезпеку для населення, ніж гостра детонація боєприпасів. Розглянуто типи пер- та поліфторованих алкільних сполук. Встановлено, що найбільш поширеними формами є довголанцюгові перфторовані сполуки ПФАС, які виявляють канцерогенні, репродуктивні та імунотоксичні властивості, є біоакумулятивними і можуть спричиняти токсичність для печінки та нирок, репродуктивну токсичність та токсичність для розвитку, ендокринні порушення, ожиріння, цукровий діабет 2 типу та різні види раку. Описано основні методи визначення мікрокількостей пер- та поліфторованих алкільних сполук включаючи газову або рідинну хроматографію, тандемну мас-спектрометрію, які є дорогими та потребують складної пробопідготовки. Наразі перевага надається твердофазній екстракції для концентрування мікрозабруднювачів, що дозволяє розширити межі їх виявлення за умови використання газової хроматографії та мас-спектрометрії. Для аналізу ПФАС у питній воді рекомендовано пакет методів тандемної хроматомасспектрометрії. Розглянуто методики контролю та підходи до очищення джерел питної води. Електрохімічні, сонохімічні, вдосконалені окиснювальні методи, а також нові гібридні методи включаючи застосування наноадсорбентів природного походження є ефективними для видалення коротколанцюгових ПФАС у лабораторних умовах, але мають обмеження у польовому застосуванні. Одним з перспективних методів очищення води у польових умовах є фотокаталіз у поєднанні з мембранною фільтрацією або електрохімічним окисненням.

Ключові слова: *мембранна фільтрація, методи визначення, мікрозабруднювачі, очищення води, поліфторалкільні сполуки (ПФАСи), токсичність*