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A BRIEF OVERVIEW OF THE PFAS POLLUTION PROBLEM IN THE ENVIRONMENT

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This study provides a comprehensive analysis of PFAS contamination in the environment. An analysis of published scientific papers has shown that PFAS are exceptionally resistant to chemical, biological, and photolytic degradation, exhibit significant mobility in water, and can be dispersed across long distances.

PFAS are known as «forever chemicals» with half-lives of thousands of years. PFAS contaminate surface water sources and can accumulate in soil and air.

Detecting and analyzing their concentrations in the environment is crucial due to their extremely prevalent presence in natural habitats, presenting risks to public health and the integrity of the ecosystem.

A review of literature sources revealed that no studies of this problem have been conducted in Kazakhstan. This paper revealed a complete lack of publications on PFAS studies. The materials presented on the websites of Kazakhstani news agencies merely reflect the results of research by foreign scientists studying PFAS in the environment and biomaterials, reflecting the global problem of PFAS contamination.

The prerequisites for this area of research are the lack of publications in Kazakhstan, the lack of PFAS monitoring, the lack of systematic studies, including foreign ones, as well as the lack of various methods for determining PFAS in environmental objects, and this requires close scientific attention and study.

Keywords: *perfluoroalkyl and polyfluoroalkyl substances (PFAS), contaminant pathways, pollution, environment, toxicological behavior.*

INTRODUCTION

Perfluoroalkyl substances (PFAS) comprise a broad group of chemicals that are applied directly in, or used during the manufacture of, non-stick surfaces, textiles, paper-based materials, food packaging, certain firefighting foams, and a wide range of other consumer and industrial products. These compounds are extensively applied in the production of consumer goods and industrial applications because of their oil and water repelling properties, their ability to withstand extreme temperatures, and their ability to minimize friction. PFAS encompass a diverse set of compounds that differ in molecular weight and exhibit various structures and functional groups, yet they are unified by a common characteristic: chains of carbon atoms in which most or all bonding sites are occupied by fluorine atoms. Over time, the extensive production and application of these substances, together with their high resistance to degradation, have led to their ubiquitous presence in the environment. At the same time, scientific research is increasingly clarifying the environmental and health impacts associated with PFAS. Among them, perfluorooctanoate (PFOA) and perfluorooctane sulfonate (PFOS) are well-known examples of PFAS that are highly mobile, persistent, and bioaccumulative,

with no evidence of transformation under environmental conditions [1–3].

Sources of PFAS can include fire ranges, military installations, airports, some manufacturing facilities, and waste landfills. Since the 1950s, PFAS have been extensively utilized in commercial and industrial products like non-stick coatings, surfactants, food packaging materials, and water-soluble foaming compounds due to their hydrophobic, lipophobic, and thermally stable qualities [4]. This has led to multiple environmental releases [5, 6].

Due to increased use, PFAS have been found in a wide range of environments, including the air, surface water, drinking water, sediment, fish, and marine mammals [7, 8]. Furthermore, numerous studies have shown that PFAS are toxic and can accumulate in humans and other biological systems [9]. PFAS are often referred to as ‘forever chemicals’ due to their extreme persistence and resistance to chemical and thermal degradation, which is attributed to the presence of multiple high-energy C-F bonds (531.5 kJ mol⁻¹) [10]. They also exhibit high mobility and have been identified in remote areas, even at locations far removed from their original sources of release [11]. Recent studies have even proposed a new planetary boundary for PFAS, as concentrations

measured in rainwater across the globe frequently surpass the strictest regulatory limits established for PFAS in drinking water [12].

The most extensively investigated PFAS (PFOA and PFOS) have been found reported in drinking water at concentrations up to several $\mu\text{g/L}$, while other PFAS occur in much lower amounts within the ng/L range. Several regulatory guideline values for drinking water have been introduced to protect human health. Under the European Union's (EU) revised Drinking Water Directive (implemented in December 2020), two regulatory limits for PFAS were introduced: $0.5 \mu\text{g/L}$ for total PFAS and $0.1 \mu\text{g/L}$ for the combined concentration of 20 priority PFAS [13]. EU member states are required to comply with regulatory provisions by 12 January 2026; however, a standardized method for determining 'total PFAS' has yet to be established.

In April 2024, the United States Environmental Protection Agency (EPA) adopted the National Primary Drinking Water Regulations, setting enforceable limits for six PFAS. The maximum allowable concentrations were established at 4 ng/L for PFOA and PFOS, and 10 ng/L for PFHxS, PFNA, and GenX and mixtures of two or more of

these substances along with perfluorobutanesulfonic acid (PFBS) have a hazard index approach [13].

MATERIALS AND METHODS

The material was based on scientific papers published by international scientists. Unfortunately, an analysis of known works revealed a complete lack of domestic research on this issue. All the studies reviewed are presented as fully as possible in this paper. The search terminology included PFAS, wastewater, surface water, and drinking water treatment, PFAS removal, and environmental and human health risks.

The primary platforms used to locate reliable sources included eLibrary, Open Science, Google Scholar, Scopus, Web of Science, ScienceDirect, and PubMed; these are major international scientometric databases aggregating scientific journal publications, patents, academic literature, articles, books, and dissertations. Additionally, the SCImago Journal Rank - a comprehensive service displaying publication citation data was utilized.

The PRISMA flow diagram [14-15] was employed to outline the literature sources used to analyze the issue (Figure 1).

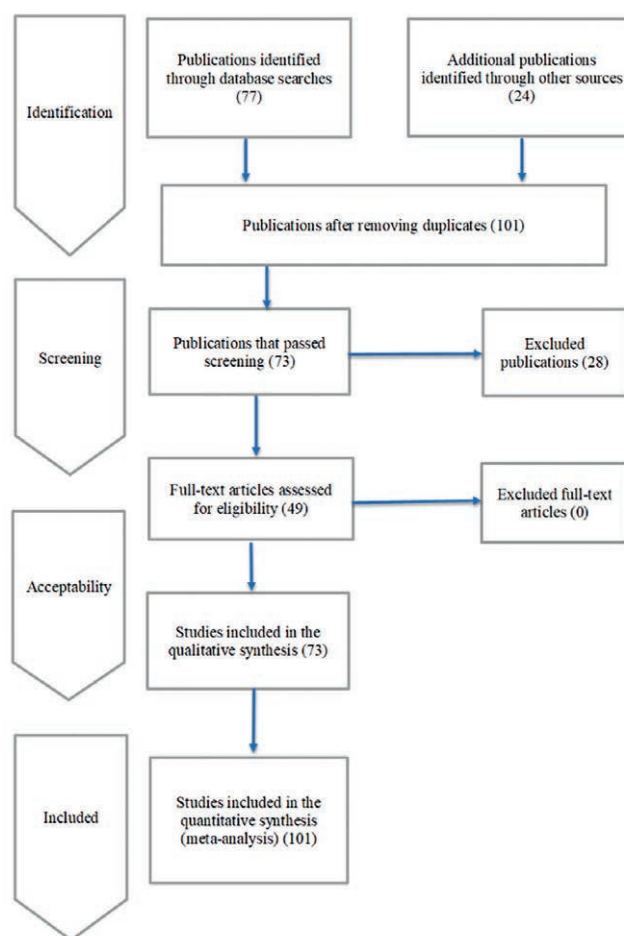


Figure 1. PRISMA flow diagram showing the literature sources used to analyze this issue [14-15].

RESULTS

PFAS are frequently described as environmentally persistent or “forever” chemicals and have recently attracted significant attention because of growing concerns regarding their possible harmful effects on ecosystems and human health [16]. PFAS compounds are extremely persistent and have high mobility: long-chain PFAS exhibit high water solubility and sorption potential, facilitating their leaching into groundwater, dispersion in surface waters, and long-range atmospheric transport [17]. Consequently, even in isolated ecosystems like the Arctic, PFAS contamination has been identified in a variety of matrices, including soil, sediments, drinking water supplies, and biota [16, 17]. As a result of their various physicochemical characteristics, PFAS raise a variety of concerns about bioaccumulation and negative effects, even though the persistence linked to the perfluorinated carbon chain is a fundamental concern [18].

PFAS’s behavior in the environment, including their molecular state and distribution, is determined by their physical and chemical qualities as well as environmental factors. Neutral and ionic molecule forms, solid and liquid states, and various habitats and biota (aqueous,

pure phase, soil/sediment, biota, and atmosphere) can all undergo partitioning. The ambient behavior of certain PFAS is further complicated by their surface-active characteristics [19,20].

Toxicological evidence demonstrates adverse effects in non-human species, including developmental toxicity, cancer, endocrine disruption, hepatotoxicity, immunotoxicity, and declined reproductive fitness [21]. Hazards associated with human health and environment, along with persistent nature, have positioned PFAS as emerging contaminants of global concern. Current regulatory efforts are increasingly emphasizing source reduction, environmental monitoring, and the development of advanced remediation strategies to mitigate their long-term ecological impacts [22,23].

PFAS are found everywhere in the environment, marking a “planetary boundary” similar to climate change or the ozone hole [24].

PFAS have been extensively utilized in a wide range of everyday consumer goods, including non-stick coatings, food wrapping, cosmetics, cookware, and hair detergents, as well as in industrial applications including surfactants and firefighting foams [25,26] (Figure 2).



Figure 2. PFAS in different consumer products [25, 26].

The Organization for Economic Co-operation and Development (OECD) indicates that more than 4,730 different PFAS compounds exist. The United States EPA DSSTox toxicity database contains 14,735 individual PFAS chemicals [27, 28], while PubChem database records over 6 million [29]. Exposure to PFAS leads to hormonal imbalances, weakened immunity, cancer, and impaired cognitive abilities [30,31]. In a 2018 *Washington Post* article, PFAS were termed “forever chemicals” [32]. The production of PFAS generates approximately \$4 billion in profits annually, while global environmental cleanup costs for PFAS are estimated at about \$17.5 trillion annually, representing 17.5% of the world’s \$100 trillion GDP in 2022 [33]. Cleaning contaminated areas is technically challenging and expensive, with annual costs ranging from €170 to €821 billion in the EEA [34,35].

PFAS gained public attention with Todd Haynes’ 2019 film *Dark Waters*, which depicted the discovery of the first evidence of this environmental contamination in 1998 at a plant in Parkersburg, West Virginia, where the DuPont chemical group manufactured Teflon.

Since the 1940s, substantial number of new PFAS compounds have been introduced, including traditional substances such as PFOS and PFOA, as well as emerging short-chain and newly identified fluorinated alternatives. These compounds vary considerably in their molecular structure, carbon chain length, and electrical charge [36,37]. PFAS have been identified in marine organisms and in a wide range of aquatic environments, namely rivers, lakes, tributaries, and groundwater, even at trace concentrations in the nanogram-per-liter (ng/L) concentration [38–40]. Despite these low concentrations, exposure to PFAS has been linked with serious health effects, including hormonal imbalance, elevated cholesterol levels, pregnancy complications, cancer, and immune system toxicity, making PFAS contamination a significant environmental and public health concern [41].

Because developmental effects are considered sensitive endpoints for long-chain PFAS, exposures during critical developmental stages (e.g., fetal and infant periods) are particularly important.

PFAS are able to penetrate the placental barrier and move across the developing fetus, and they may also be transmitted from mother to infant via breast milk. Among the general population, breastfed infants can experience higher exposure to long-chain PFAS than their mothers. Moreover, infant exposure can be greater than that of adults when formula is prepared using contaminated water or when breastfeeding mothers consume contaminated drinking water [42].

PFAS may also adsorb onto micro- and nanoplastics, potentially intensifying their harmful effects [43]. PFAS compounds have been successively recognized as persistent organic pollutants (POPs) under the Stockholm Convention: PFOS in 2009, PFOA and related compounds in 2019, and PFHxS with its associated chemicals in 2022

[4, 44]. In addition, toxic long-chain perfluorocarboxylic acids (LC-PFCAs) were scheduled for consideration by the Conference of the Parties in May 2025.

Over the last twenty years, the production of specific PFAS compounds has shifted toward Asia, where oversight and regulation are less rigorous [11]. If emissions continue, PFAS will accumulate further in the environment creating significant challenges for a circular economy in the world.

According to the revised EU Drinking Water Directive (DWD) EU 2020/2184, the maximum limit of the total PFAS concentration in drinking water is up to 0.5 µg/L. However, concentrations exceeding 10,000 ng/L of water have been found at 640 locations in the EU and the UK [11].

Few peer-reviewed studies have evaluated PFAS levels in tap water after point-of-use or outdoor wastewater treatment processes, and only five of these have assessed removal efficiency under real-world conditions. Furthermore, the reported results suggest that not all filters were effective, particularly for short-chain PFAS [45, 46].

In this study, 81 PFAS were examined in tap water derived from three major water sources in East China, a region recognized as a global hotspot for PFAS emissions. Comprehensive quantitative analysis identified 64 PFAS, the highest number reported so far, including 28 newly detected compounds quantified for the first time in Chinese tap water. The conventional water treatment strategies are not that effective, so PFAS concentrations and profiles in tap water closely reflected those in the source water and varied with seasonal changes. As a result, contamination present in raw water was directly conveyed to tap water, with total PFAS concentrations reaching as high as 8970.3 ng/L [47].

In the United States, drinking water quality in Massachusetts is regulated by the Massachusetts Department of Environmental Protection (MassDEP), which has set a mandatory maximum contaminant level (MCL) for PFAS to ensure safe daily and lifetime exposure. These standards limit the combined concentration of six PFAS in drinking water to 20 parts per trillion (ppt), equivalent to nanograms per liter (ng/L). These six PFAS include the following (Table 1):

Table 1. Abbreviations for some PFAS compounds

PFAS Name	Abbreviation
Perfluorohexane sulfonic acid	PFHxS
Perfluoroheptanoic acid	PFHpA
Perfluorooctanoic acid	PFOA
Perfluorooctane sulfonic acid	PFOS
Perfluorononanoic acid	PFNA
Perfluorodecanoic acid	PFDA

The Danish Environmental Protection Agency recommends that drinking water contain no more than 2 ng/L. The highest contamination level has been recorded in Zwijndrecht, Belgium, where a PFAS manufacturing plant is located. Concentrations of up to 73 million ng/L have been observed there - 36.5 million times the recommended safe level. Currently, much of the global funding allocated to addressing PFAS is related to

environmental cleanup efforts [35]. These results raise serious concerns due to the persistence, toxicological profile of PFAS and their ability to bioaccumulate in the body and food chain [48].

As PFAS move along commercial pathways from primary producer to commercial consumer to final disposer, releases into the environment occur through both controlled and uncontrolled waste streams (Figure 3).

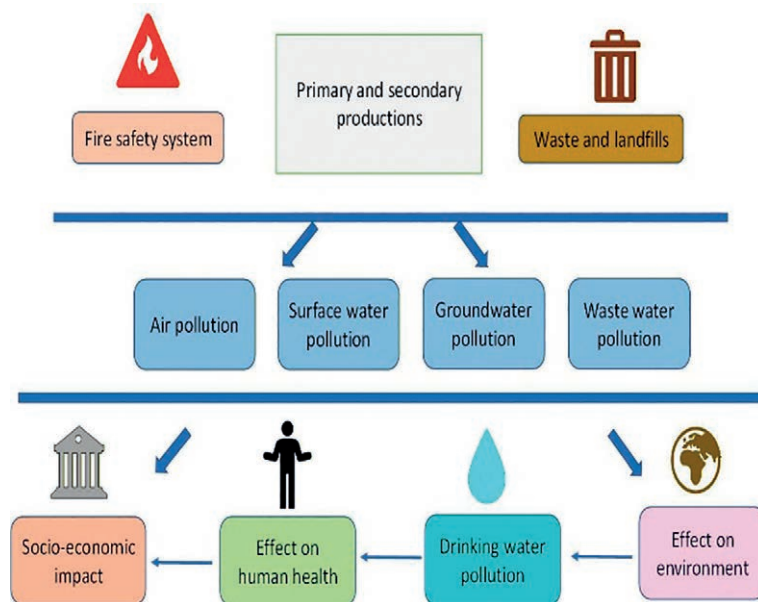


Figure 3. The ways of PFAS to enter the environment.

The main sources of PFAS in aquatic environments are wastewater discharges from treatment plants [49, 50], emissions from manufacturing facilities [51, 52], industrial plants, and landfill leachate [53].

Industrial PFAS sources include both primary and secondary manufacturing facilities. Primary facilities consist of those that synthesize PFAS-based products, produce chemical feedstocks or finished articles, and use PFAS as processing agents in fluoropolymer manufacturing. PFAS-containing process aids are not designed to be part of the final product; however, trace residues may remain [54, 55].

There is a likelihood that secondary manufacturing facilities utilize PFAS-containing substances and fluoropolymers supplied by primary production plants in industrial operations, including the coating of finished products.

According to the U.S. Environmental Protection Agency [56–58], PFAS manufacturers and formulators are categorized within the Organic Chemicals, Plastics, and Synthetic Fibers (OCPSF) point source category. This category covers a wide variety of industries, raw materials, and production processes that can generate or utilize PFAS.

Common mechanisms and pathways for PFAS releases at industrial facilities are shown in Figure 3. Major sources of PFAS include wastewater discharges, on- and off-site solid waste disposal, accidental emissions including leaks and spills, fire-fighting aqueous film-forming foam (AFFF), and stack/fugitive emissions. PFAS can be deposited on surface water bodies and soil systems (followed by leaching and migration to groundwater) related to the facility [59–62] by stack emissions, and transported by air both short and long distances. Industrial facilities may include areas where fire training or emergency response activities involving AFFF have taken place, as well as AFFF storage locations and building-integrated fire suppression systems. Similar to other AFFF release sites, these facilities may also contain co-occurring contaminants such as solvents or petroleum hydrocarbons, which can influence the environmental fate and transport of PFAS.

Identified environmental pathways for PFAS migration include [42]: leaching from soil, advection and dispersion from water and air, atmospheric deposition, and diffusion in water/air. Through these pathways, PFAS can be transported through the atmosphere and deposited in distant locations, resulting in measurable accumulation far from their original sources.

The movement of PFAS through unsaturated soils under rainfall or irrigation conditions varies by site and is influenced by both environmental factors and PFAS molecular characteristics. High PFAS concentrations can lead to micelle formation and its growth, potentially increasing their adsorption behavior on minerals and carbon surfaces. The persistence of many PFAS degradation products contributes to their widespread presence in the environment. Moreover, the increasing number of PFAS that undergo partial degradation further complicates their detection and remediation [63].

PFAS distribution, transport, and transformation occur in a variety of environments. Regulatory attention has focused on PFOS and PFOA due to their toxic nature and environmental persistence, even at trace concentrations [42]. The transformation pathways of some PFAS are well characterized, many others degrade through unknown mechanisms, further expanding the already extensive list of PFAS. For the PFAS that are identified, data on their potential ecological impacts and effects on ecosystem services remain limited. Only a small fraction of these forever chemicals has been thoroughly investigated in ecotoxicological studies, with PFOA and PFOS alone representing 21% and 39% of the ECOTOX database, respectively [64].

At the same time, most research on PFAS focuses on concentration studies, while the removal of PFAS has been poorly explored [37, 65].

The number of emerging PFAS with limited information on their physical, chemical, and toxicological properties is rapidly growing. These compounds exhibit diverse chemical structures, varying volatility and solubility, and uncertain potential impacts from exposure.

Kazakhstan, geographically located in the heart of Eurasia, experiences a sharply continental climate, including hot summers. The city of Almaty is characterized by a growing population, expanding construction, and agriculture. The development of Kazakhstan's capital, Astana, has increased anthropogenic pressure on surface water sources, intensifying their role for recreation purposes. The impact of municipal and industrial activities is accompanied by pollution of both wastewater and surface waters. Therefore, it is important to study the spread of PFAS within the "wastewater-surface water" system to understand the scale of the problem and consider it when developing measures to clean these water bodies. For these reasons, the city's water bodies represent a valuable system for studying the presence of PFAS. According to Kazakhstani experts [66], improper management of municipal wastewater in growing urban areas of Kazakhstan leads to the contamination of rivers with various substances. Since 2008, Kazakhstan has significantly expanded its monitoring infrastructure, yet PFAS monitoring of water resources is not conducted.

At the national level, the Republic has ratified the Stockholm Convention, which implements plans for

the management and implementation of modern eco-monitoring methods, but PFAS are not being studied in the environment [67].

The analytical environmental agency Greenwomen has prepared a review on PFAS in Kazakhstan and the world. The article notes that Kazakhstan ratified the Stockholm Convention on November 9, 2007 [67]. The effective dates of amendments to Annexes A, B or C to the Convention for PFAS in Kazakhstan include: PFHxS - November 16, 2023. PFOA – December 3, 2020. Another category of PFAS is used in Kazakhstan in the form of gases and liquids, for example, refrigerants in refrigerators or air conditioning systems. In 2024, Kazakhstan planned to build an industrial complex for the processing of refrigeration equipment and the thermal removal of ODS (ozone depleting substances) and persistent pollutants POPS and the complex is expected to operate in 2026 [68].

The materials of Kazakhstani news agencies only reflect the results of research by foreign scientists, which show the presence of PFAS in the environment and biomaterials, reflecting the global trend towards pollution [69-73].

Issues related to PFAS contamination of water bodies worldwide raise concerns about addressing environmental, biological, social, and economic challenges.

DISCUSSION

Although global data on PFAS concentrations in water has been published, similar studies are lacking in Kazakhstan. The only available research pertains to PFAS content in sports gloves produced in Russia [67].

Unfortunately, most of the global studies on PFAS do not meet established quality standards.

Based on the principle underlying the Water Safety Plan, which involves controlling contaminants at their source, it would be prudent to conduct research aimed at improving wastewater treatment methods for removing PFAS from their main pathway into the aquatic environment. Environmental impact assessment is complicated by the vast number of functionally diverse PFAS and is further complicated by their presence as complex mixtures.

All this leads to an understanding of the need for regular monitoring of PFAS content in environmental water bodies, adaptation of existing methods for surface water samples in Kazakhstan and ultimately ensuring water purification from PFAS and developing appropriate legislative and regulatory frameworks tailored to local conditions.

CONCLUSION

Technological progress and active industrialization lead to various environmental problems and the number of environmental disasters continues to grow. Among the most serious challenges requiring urgent solutions are the health risks posed by per - and polyfluoroalkyl substances (PFAS), their contamination of water resources and the problem of their disposal.

These problems require immediate attention, active State policy and joint concerted efforts. At the same time, the problem of reducing the health risks associated with PFAS requires a multi-pronged approach that should combine the following areas:

1. Regulatory measures: Governments should ensure the development and enforcement of legislation to control the production and use of PFAS, so that industrial enterprises switch to safer alternatives.

2. Research and innovation: Investments in research to develop effective technologies for removing PFAS from water sources and contaminated sites are crucial.

3. Public awareness: Informing consumers about the dangers of PFAS and promoting PFAS-free products can help shift the market towards safer alternatives.

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REFERENCES

- USEPA. 2003. Perfluorooctanoic Acid (PFOA), Fluorinated Telomers; Request for Comment, Solicitation of Interested Parties for Enforceable Consent Agreement Development, and Notice of Public Meeting. 68 Federal Register 18626. (Washington D.C.: USEPA). April 16.NTP 2016.
- NTP. 2016. NTP Monograph on Immunotoxicity Associated with Exposure to Perfluorooctanoic Acid (PFOA) or Perfluorooctane Sulfonate (PFOS). (Division of the National Toxicology Program Office of Health Assessment and Translation, National Institute of Environmental Health Sciences). September. https://ntp.niehs.nih.gov/ntp/ohat/pfoa_pfos/pfoa_pfosmonograph_508.pdf
- Smith, J. W. N., Beuthe, B., Dunk, M., Demeure, S., Carmona, J. M. M., Medve, A., & Slenders, H. (2016). Environmental fate and effects of poly-and perfluoroalkyl substances (PFAS). Environmental science for the European refining industry, concawe, report, (8/16).
- Wang, Y. Q., Hu, L. X., Liu, T., Zhao, J. H., Yang, Y. Y., Liu, Y. S., & Ying, G. G. (2022). Per-and polyfluoroalkyl substances (PFAS) in drinking water system: Target and non-target screening and removal assessment. Environment International, 163, 107219. <https://doi.org/10.1016/j.envint.2022.107219>
- X. Trier, K. Granby, J.H. Christensen. Polyfluorinated surfactants (PFS) in paper and board coatings for food packaging. Environ. Sci. Pollut. Res., 18 (7) (2011), pp. 1108-1120
- Wang, Z., DeWitt, J. C., Higgins, C. P., & Cousins, I. T. (2017). A never-ending story of per-and polyfluoroalkyl substances (PFASs) Environ. Sci. Technol., 51 (5), pp. 2508-2518.
- Chow, S. J., Ojeda, N., Jacangelo, J. G., & Schwab, K. J. (2021). Detection of ultrashort-chain and other per-and polyfluoroalkyl substances (PFAS) in US bottled water. Water research, 201, 117292.
- Podder, A., Sadmani, A. A., Reinhart, D., Chang, N. B., & Goel, R. (2021). Per and poly-fluoroalkyl substances (PFAS) as a contaminant of emerging concern in surface water: A transboundary review of their occurrences and toxicity effects. Journal of hazardous materials, 419, 126361.
- Pan, C. G., Zhao, J. L., Liu, Y. S., Zhang, Q. Q., Chen, Z. F., Lai, H. J., ... & Ying, G. G. Bioaccumulation and risk assessment of per- and polyfluoroalkyl substances in wild freshwater fish from rivers in the Pearl River Delta region, South China. Ecotoxicol. Environ. Saf., 107 (2014), pp. 192-199
- Niu, Y., Tan, H., & Hui, S. E. Ash-related issues during biomass combustion: Alkali-induced slagging, silicate melt-induced slagging (ash fusion), agglomeration, corrosion, ash utilization, and related countermeasures. Progress in Energy and Combustion Science. 2016, Volume: Volume 52. Pages: 1-61.
- MacKeown, H., Magi, E., Di Carro, M., & Benedetti, B. Removal of perfluoroalkyl and polyfluoroalkyl substances from tap water by means of point-of-use treatment: A review. Science of The Total Environment. Volume 954, 1 December 2024, 176764. <https://doi.org/10.1016/j.scitotenv.2024.176764>.
- Cousins, I. T., Johansson, J. H., Salter, M. E., Sha, B., & Scheringer, M. Outside the Safe Operating Space of a New Planetary Boundary for Per- and Polyfluoroalkyl Substances (PFAS). Environmental Science & Technology, 2022, Vol 56/Issue 16
- EPA, Per- and Polyfluoroalkyl Substances (PFAS). Final PFAS National Primary Drinking Water Regulation 2024, <https://www.epa.gov/sdwa/and-polyfluoroalkyl-substances-pfas>
- Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & Prisma Group (2009). Preferred Reporting Items for Systematic Reviews and MetaAnalyses: The PRISMA Statement. PLoS Med 6(6): e1000097. <https://doi:10.1371/journal.pmed1000097>,
- PRISMA. Last accessed 20 June, 2026. www.prisma-statement.org.
- Kwiatkowski, C.F., Andrews, D.Q., Birnbaum, L.S., Bruton, T.A., DeWitt, J.C., Knappe, D.R.U., ... & Wang, Z. (2020). Scientific basis for managing PFAS as a chemical class. Environmental Science & Technology Letters, 7(8), 532–543.
- Giesy, J.P. & Kannan, K. (2001). Global distribution of perfluorooctane sulfonate in wildlife. Environmental Science & Technology, 35(7), 1339–1342.
- Marina G. Evitch, Mary J. B. Davis, James P. McCord, Brad Acree, Jill A. Aukerman, Detlef R. W. Knappe, Andrew B. Lindstrom, Thomas F. Spaeth, Caroline T. Stevens, Mark J. Strynar, Zhanyun Wang, Eric J. Weber, W. Matthew Henderson, John W. Washington. Per- and polyfluoroalkyl substances in the environment. Science. 2022 Feb 4;375(6580):eabg9065. <https://doi: 10.1126/science.abg9065>.
- ITRC. 2023. Fate and Transport of Per- and Polyfluoroalkyl Substances (PFAS). https://pfas-1.itrcweb.org/wp-content/uploads/2023/10/FT_PFAS_FactSheet_Sept_2023_final.pdf.

20. Routti, H., Letcher, R.J., Arukwe, A., van Bavel, B., Yoccoz, N.G. & Jenssen, B.M. (2017). Influence of body condition on tissue distribution of perfluoroalkyl substances in Arctic fox (*Vulpes lagopus*). *Environmental Science & Technology*, 51(12), 6677–6686.
21. Kumar, A., Rothstein, J. C., Chen, Y., Zhang, H., & Zhao, Y. (2025). Experimental Raman spectra analysis of selected PFAS compounds: Comparison with DFT predictions. *Journal of Hazardous Materials*, 138704.
22. Lau, C., Anitole, K., Hodes, C., Lai, D., Pfahles-Hutchens, A. & Seed, J. (2007). Perfluoroalkyl acids: A review of monitoring and toxicological findings. *Toxicological Sciences*, 99(2), 366–394.
23. UNEP. (2022). Global governance of per- and polyfluoroalkyl substances (PFAS). United Nations Environment Programme.
24. European Environmental Agency, Treatment of drinking water to remove PFAS (Signal), 2024. <https://www.eea.europa.eu/en/european-zero-pollution-dashboards/indicators/treatment-of-drinking-water-to-remove-pfas-signal>.
25. Das, S. , and Ronen A.. 2022. "A Review on Removal and Destruction of Per- and Polyfluoroalkyl Substances (PFAS) by Novel Membranes." *Membranes* 12, no. 7: 662.
26. Xue, J. , Verstraete W., Ni B.-J., et al. 2025. "Rethink Biosolids: Risks and Opportunities in the Circular Economy." *Chemical Engineering Journal* 510: 161749.
27. Buck, R. C., Korzeniowski, S. H., Laganis, E., & Adamsky, F. (2021). Identification and classification of commercially relevant per-and poly-fluoroalkyl substances (PFAS). *Integrated environmental assessment and management*, 17(5), 1045-1055. <https://doi.org/10.1002/ieam.4450>
28. Schymanski, E. L., Zhang, J., Thiessen, P. A., Chirsir, P., Kondic, T., & Bolton, E. E. (2023). Per-and polyfluoroalkyl substances (PFAS) in PubChem: 7 million and growing. *Environmental science & technology*, 57(44), 16918-16928. <https://doi:10.1021/acs.est.3c04855>
29. National Institute of Environmental Health and Science. Last accessed 10 June, 2026. <https://www.niehs.nih.gov/health/topics/agents/pfc>
30. Ames, J. L., Sharma, V., & Lyall, K. (2025). Effects of early-life PFAS exposure on child neurodevelopment: a review of the evidence and research gaps. *Current environmental health reports*, 12(1), 9. <https://doi: 10.1007/s40572-024-00464-5>.
31. PFAS. Last accessed 3 June, 2026. https://en.wikipedia.org/wiki/Per_and_polyfluoroalkyl_substances
32. Washington Post, Joseph G. A. These toxic chemicals are everywhere – even in your body (2018). https://www.washingtonpost.com/opinions/these-toxic-chemicals-are-everywhere-and-they-wont-ever-go-away/2018/01/02/82e7e48a-e4ee-11e7-a65d-1ac0fd7f097e_story.html
33. Crone, B. C. , Speth T. F., Wahman D. G., et al. 2019. "Occurrence of Per- and Polyfluoroalkyl Substances (PFAS) in Source Water and Their Treatment in Drinking Water." *Critical Reviews in Environmental Science and Technology* 49, no. 24: 2359–2396
34. Hara-Yamamura, H. , Inoue K., Matsumoto T., Honda R., Ninomiya K., and Yamamura H.. 2022. "Rejection of Perfluorooctanoic Acid (PFOA) and Perfluorooctane Sulfonate (PFOS) by Severely Chlorine Damaged RO Membranes With Different Salt Rejection Ratios." *Chemical Engineering Journal* 446: 137398.
35. Lenka, S. P. , Kah M., and Padhye L. P. 2021. "A Review of the Occurrence, Transformation, and Removal of Poly- and Perfluoroalkyl Substances (PFAS) in Wastewater Treatment Plants." *Water Research* 199: 117187.
36. Zhang, J. , Huang Z., Gao L., Gray S., and Xie Z.. 2022. "Study of MOF Incorporated Dual Layer Membrane With Enhanced Removal of Ammonia and Per-/Poly-Fluoroalkyl Substances (PFAS) in Landfill Leachate Treatment." *Science of the Total Environment* 806: 151207.
37. Munoz G, Budzinski H, Babut M, Drouineau H, Lauzent M, Menach KL, et al. (August 2017). Evidence for the Trophic Transfer of Perfluoroalkylated Substances in a Temperate Macrotidal Estuary. *Environmental Science & Technology*. 51 (15): 8450–8459. doi:10.1021/acs.est.7b02399. PMID 28679050
38. Johnson, J.K., Michael Salerno, K., Schlesinger, D.R. et al. Removing forever chemicals via amphiphilic functionalized membranes. *npj Clean Water* 5, 55 (2022). <https://doi.org/10.1038/s41545-022-00193-y>
39. Chen, W. , Liu M., Ding M., Zhang L., and Dai S.. 2023. "Advanced Thin-Film Composite Polyamide Membrane for Precise Trace Short-Chain PFAS Sieving: Solution, Environment and Fouling Effects." *Process Safety and Environmental Protection* 169: 493–503.
40. ITRC (2023). Human and Ecological Health Effects and Risk Assessment of Per- and Polyfluoroalkyl Substances (PFAS). https://pfas-1.itrcweb.org/wp-content/uploads/2023/10/HH_Eco_PFAS_Fact-Sheet_Sept2023_final.pdf
41. Samaei, S. H.-A. , Mojahednia P., Chen J., et al. 2025. "What Does the "Trojan Horse" Carry. The Pollutants Associated With Microplastics/Nanoplastics in Water Environments." *ACS ES&T Water* 5, no. 4: 1530–1545.
42. Li, H. , Junker A. L., Wen J., et al. 2023. "A Recent Overview of Per- and Polyfluoroalkyl Substances (PFAS) Removal by Functional Framework Materials." *Chemical Engineering Journal* 452: 139202.
43. Tow, E. W. , Ersan M. S., Kum S., et al. 2021. "Managing and Treating Per- and Polyfluoroalkyl Substances (PFAS) in Membrane Concentrates." *AWWA Water Science* 3, no. 5: e1233.
44. European Chemical Agency. Perfluoroalkyl Chemicals. <https://echa.europa.eu/hot-topics/perfluoroalkyl-chemicals-pfas>.
45. Zhang, X., Wang, D., Wang, K., Yang, Z., Ai, M., & Zhang, Y. (2025). Legacy and Novel Per-and Polyfluoroalkyl Substances in Tap Water from East China: Impact from Water Sources and Risk Mitigation by Household Purifiers. *Environmental Science & Technology*, 59(32), 17210-17221. <https://pubs.acs.org/doi/10.1021/acs.est.5c03293>.
46. Ecology. https://www.vedomosti.ru/ecology/protection_nature/articles/2023/08/03/988319.
47. IPEN. Last accessed 10 June, 2026. https://ipen.org/sites/default/files/documents/ipen-pfas-2021-v1_6w-ru.pdf
48. Pan, C. G., Liu, Y. S., & Ying, G. G. (2016). Perfluoroalkyl substances (PFASs) in wastewater treatment plants and drinking water treatment plants: Removal efficiency and exposure risk. *Water research*, 106, 562-570.
49. P. Jacob, K.A. Barzen-Hanson, D.E. Helbling. Target and Nontarget Analysis of Per- and Polyfluoroalkyl Substances in Wastewater from Electronics Fabrication Facilities. *Environ. Sci. Technol.*, 55 (4) (2021), pp. 2346-2356.

50. Y.i. Wang, N. Yu, X. Zhu, H. Guo, J. Ji-ang, X. Wang, W. Shi, J. Wu, H. Yu, S.i. Wei. Suspect and Nontarget Screening of Per- and Polyfluoroalkyl Substances in Wastewater from a Fluorochemical Manufacturing Park. *Environ. Sci. Technol.*, 52 (19) (2018), pp. 11007-11016.
51. I. Fuertes, S. Gomez-Lavin, M.P. Elizalde, A. Urtiaga. Perfluorinated alkyl substances (PFASs) in northern Spain municipal solid waste landfill leachates. *Chemosphere*, 168 (2017), pp. 399-407).
52. Buck, Robert C., Stephen H. Korzeniowski, Evan Laganis, and Frank Adamsky. 2021. "Identification and classification of commercially relevant per- and poly-fluoroalkyl substances (PFAS)." *Integrated Environmental Assessment and Management* 17 (5):1045-1055. <https://doi.org/10.1002/ieam.4450>
53. Buckley, Thomas, Xiaoyong Xu, Victor Rudolph, Mahshid Firouzi, and Pradeep Shukla. 2021. "Review of foam fractionation as a water treatment technology." *Separation Science and Technology*:1-30.10.1080/01496395.2021.1946698).
54. USEPA. 2021. Multi-Industry Per- and Polyfluoroalkyl Substances (PFAS) Study – 2021 Preliminary Report. EPA-821-R-21-004. Washington, DC: Office of Water U.S Environmental Protection Agency.https://www.epa.gov/system/files/documents/2021-09/multi-industry-pfas-study_preliminary-2021-report_508_2021.09.08.pdf.
55. USEPA. 2021. "PFAS Explained." Last Modified October 18, 2021. accessed 2021.<https://www.epa.gov/pfas/pfas-explained>; USEPA. 2021. "Human Health Toxicity Assessments for GenX Chemicals." Last Modified November 9, 2021. accessed 2021.<https://www.epa.gov/chemical-research/human-health-toxicity-assessments-genx-chemicals>;
56. USEPA. 2021. Proposed Approaches to the Derivation of a Draft Maximum Contaminant Level Goal for Perfluorooctanoic Acid (PFOA) (CASRN 335-67-1) in Drinking Water. External Peer Review Draft. EPA 822-D-21-001. Washington, D.C.: U.S. Environmental Protection Agency Office of Water (4304T),
57. Davis, Katherine L., Michael D. Aucoin, Barbara S. Larsen, Mary A. Kaiser, and Andrew S. Hartten. 2007. Transport of ammonium perfluorooctanoate in environmental media near a fluoropolymer manufacturing facility. *Chemosphere* 67 (10):2011-2019. <https://doi.org/10.1016/j.chemosphere.2006.11.049>;
58. de la Torre, Adrián, Irene Navarro, Paloma Sanz, and María de los Ángeles Martínez. 2019. "Occurrence and human exposure assessment of perfluorinated substances in house dust from three European countries." *Science of The Total Environment* 685:308-314.<https://doi.org/10.1016/j.scitotenv.2019.05.463>;
59. De Silva, Amila O., James M. Armitage, Thomas A. Bruton, Clifton Dassuncao, Wendy Heiger-Bernays, Xindi C. Hu, Anna Kärrman, Barry Kelly, Carla Ng, Anna Robuck, Mei Sun, Thomas F. Webster, and Elsie M. Sunderland. 2021. "PFAS Exposure Pathways for Humans and Wildlife: A Synthesis of Current Knowledge and Key Gaps in Understanding." *Environmental Toxicology and Chemistry* 40 (3):631-657. <https://doi.org/10.1002/etc.4935>;
60. Shin, Hyeong-Moo, Verónica M. Vieira, P. Barry Ryan, Russell Detwiler, Brett Sanders, Kyle Steenland, and Scott M. Bartell. 2011. "Environmental Fate and Transport Modeling for Perfluorooctanoic Acid Emitted from the Washington Works Facility in West Virginia." *Environmental Science & Technology* 45 (4):1435-1442. 10.1021/es102769t657.<https://doi.org/10.1002/etc.4935>;
61. Jiao S., Shi Q., Gan Q., Uptake, accumulation, and metabolism of PFAS in plants and health prospects: a critical review. *Critical Reviews in Environmental Science and Engineering*, 1–32 (2020).
62. Ankli, G. T., et al., Environmental Risk Assessment of Per- and Polyfluoroalkyl Substances: Current State of the Science and Proposed Way Forward. *Environmental Toxicology and Chemistry*, n/a, (2020).
63. Kazakhstan Environmental Performance Reviews: Third Review https://unece.org/sites/default/files/2021-08/ECE_CEP_185_Rus.pdf
64. Bonn PAC, Hofman JAMH, & van Der Hoek JP (2000). Scaling control of RO membranes and direct treatment of surface water. *Desalination*, 132(10), 109–119.
65. Boo C, Wang Y, Zucker I, Choo Y, Osuji CO, & Elimelech M (2018). High performance nanofiltration membrane for effective removal of perfluoroalkyl substances at high water recovery. *Environmental Science and Technology*, 52, 7279–7288. 10.1021/acs.est.8b01040 [PubMed: 29851340]].
66. Miranda, D. A., Benskin, J. P., Awad, R., Lepoint, G., Leonel, J., & Hatje, V. (2021). Bioaccumulation of Per- and polyfluoroalkyl substances (PFASs) in a tropical estuarine food web. *Science of the Total Environment*, 754, 142146.
67. Regional Bulletin. NGO networks on chemical safety EECCA. (2024). https://ipen.org/wp-content/uploads/2026/03/2024_2_byulleten_ipen_vekca_iyul_2024.pdf.
68. UNIDO, Construction of an Industrial Complex for the Processing of Refrigeration/Air Conditioning Equipment and Thermal Destruction of ODS/POPs in Kazakhstan https://www.waste-management.org/en/success_story/construction_of_an_industrial_complex_for_the_processing/
69. High concentrations of chemicals found in fish-based pet food (2026). <https://www.zakon.kz/mir/6508807-v-kormakh-s-ryboy-dlya-domashnikh-zhivotnykh-vyyavili-bolshuyu-kontsentratsiyu-khimikatov.html>.
70. Dangerous «forever chemicals» found in one in five children (2023) <https://standard.kz/ru/post/opasnye-vecnyeximikaty-naideny-u-kazdogo-pyatogo-rebenka>.
71. Azamatkhan Akhmadov (2025). Scientists have identified the liver's worst enemy, and it isn't alcohol. <https://tengrinews.kz/healthy/uchenyie-nashli-glavnyiy-vrag-pecheni-i-eto-ne-spirtnoe-578284/>.
72. A simple way to combat «forever chemicals» has been found. Last updated February 2025. <https://nauka.kz/>
73. National report of the Ministry of Ecology, Geology and Bioresources for 2022

ҚОРШАҒАН ОРТАНЫҢ PFAS ЗАТТАРЫМЕН ЛАСТАНУ МӘСЕЛЕСІНЕ ҚЫСҚАША ШОЛУ

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Бұл зерттеу қоршаған ортадағы PFAS ластануының кешенді талдауын ұсынады. Жарияланған ғылыми мақалаларды талдау PFAS химиялық, биологиялық және фотолиттік ыдырауға ерекше төзімді екенін, суда айтарлықтай қозғалғыштық танытатынын және ұзақ қашықтыққа таралуы мүмкін екенін көрсетті.

PFAS мыңдаған жылдар бойы жартылай ыдырау кезеңдері бар «мәңгілік химиялық заттар» ретінде белгілі. PFAS жер үсті су көздерін ластайды және топырақ пен ауада жиналуы мүмкін.

Олардың қоршаған ортадағы концентрациясын анықтау және талдау өте маңызды, себебі олар табиғи мекендеу орталарында өте кең таралған, бұл қоғамдық денсаулыққа және экожүйенің тұтастығына қауіп төндіреді.

Әдеби шолу PFAS зерттеулері бойынша жарияланымдардың мүлдем жоқтығын көрсетті. Қазақстандық ақпарат агенттіктерінің веб-сайтарында ұсынылған материалдар қоршаған ортадағы PFAS пен биоматериалдарды зерттейтін шетелдік ғалымдардың зерттеулерінің нәтижелерін ғана көрсетеді, бұл PFAS ластануының жаһандық мәселесін көрсетеді.

Зерттеудің бұл бағытының алғышарттары – Қазақстанда жарияланымдардың аздығы, PFAS мониторингінің болмауы, жүйелі зерттеулердің, соның ішінде шетелдік зерттеулердің болмауы, сондай-ақ қоршаған орта нысандарындағы PFAS анықтаудың әртүрлі әдістерінің болмауы, және бұл мұқият ғылыми назар аударуды және зерттеуді қажет етеді.

Түйін сөздер: перфторалкил және полифторалкил заттар (PFAS), ластанушы жолдар, ластану, қоршаған орта, токсикологиялық мінез-құлық.

КРАТКИЙ ОБЗОР ПРОБЛЕМЫ ЗАГРЯЗНЕНИЯ ОКРУЖАЮЩЕЙ СРЕДЫ ПФАС

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В данном исследовании представлен всесторонний анализ загрязнения окружающей среды ПФАС. Анализ опубликованных научных работ показал, что ПФАС обладают исключительной устойчивостью к химической, биологической и фотолитической деградации, проявляют значительную подвижность в воде и могут распространяться на большие расстояния.

ПФАС известны как «вечные химические вещества» с периодом полураспада в тысячи лет. ПФАС загрязняют поверхностные водные источники и могут накапливаться в почве и воздухе.

Выявление и анализ их концентраций в окружающей среде имеют решающее значение из-за их чрезвычайно широкого распространения в природных местообитаниях, представляющих опасность для здоровья населения и целостности экосистемы.

Обзор литературных источников показал, что в Казахстане не проводились исследования по этой проблеме. Обзор литературы выявил полное отсутствие публикаций по исследованиям ПФАС. Материалы, представленные на сайтах казахстанских информационных агентств, лишь отражают результаты исследований зарубежных ученых, изучающих ПФАС в окружающей среде и биоматериалах, что отражает глобальную проблему загрязнения ПФАС.

Предпосылками для данного направления исследований являются недостаток публикаций в Казахстане, отсутствие мониторинга ПФАС, отсутствие систематических исследований, в том числе зарубежных, а также отсутствие разнообразных методов определения ПФАС в объектах окружающей среды, что требует пристального научного внимания и изучения.

Ключевые слова: перфторалкильные и полифторалкильные вещества (ПФАС), пути распространения загрязняющих веществ, загрязнение, окружающая среда, токсикологическое поведение.