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Research progress on the transportation of poly- and perfluoroalkyl substances (PFASs) in freshwater based on CiteSpace

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ABSTRACT

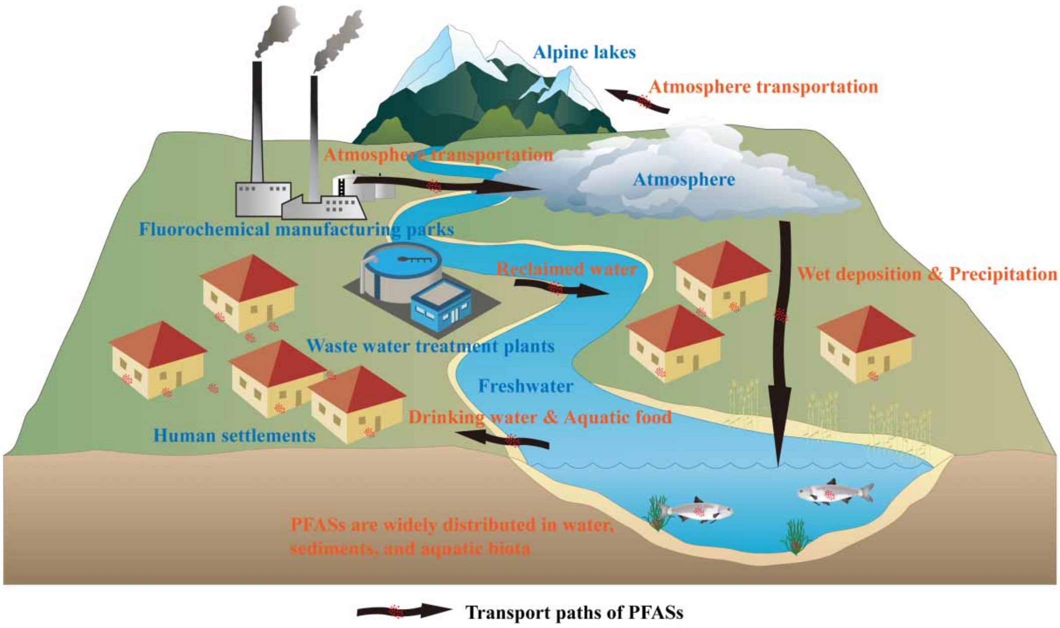
Poly- and perfluoroalkyl substances (PFASs) have garnered extensive attention due to their dissolubility, stability, hydrophobicity, and oleophobicity, contributing to long-range transport of PFASs in the water. As an important part of the blue-green space system, freshwater plays a decisive role in ensuring environmental health. Hence, a comprehensive analysis of the current studies regarding the transportation of PFASs in freshwater is highly important for ecotoxicological assessment and pollution control. To explore research progress and hotspots of transportation of PFASs in freshwater, CiteSpace software was utilized in this literature to conduct publication growth, analysis of countries/regionss, analysis of publishing institutions, co-citation analysis, keywords bursting analysis, and keywords timeline analysis. The publication trends of the transportation of PFASs in freshwater were divided into the embryonic period (2005–2014) and the developing period (2015–2023). Institutions and authors from China were found to publish most literature, indicating China places a significant emphasis on the assessment of risks of PFASs in freshwater environments. Research hotspots shifted from transport behaviors and mechanisms to risk assessment and multimedia transportation. Understanding the transportation of PFASs in freshwater is crucial for assessing environmental impacts, ensuring water resource sustainability, and contributing to the development of management practices prioritizing sustainability, energy efficiency, and environmental responsibility.

Key words: CiteSpace, freshwater, PFASs, research hotspots, transportation, visualization analysis

HIGHLIGHTS

- PFASs' facilitating freshwater transport is crucial for the blue-green system.
- Comprehensive analysis includes publications, cooperation, co-citation, and keyword networks.
- Publications are analyzed over embryonic (2005–2014) and developing (2015–2023) periods.
- China shows notable dedication to the transportation of PFASs in freshwater.
- Hotspots shift from PFAS' transport behavior to risk assessment and multimedia transportation.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Poly- and perfluoroalkyl substances (PFASs) are a family of emerging organic contaminants that exist widely in aquatic environments. PFASs are hydrophobic, oleophobic, and chemically and thermally stable owing to the unique properties of C–F bonds (Li *et al.* 2023). Since the 1940s, PFASs and their precursors have been widely produced and utilized in various industrial applications and commercial products such as aqueous film-forming foam (AFFF), personal care products, textiles, and materials resistant to greases, dirt, and water (Dasu *et al.* 2022). Freshwater includes rivers and their branches, creeks, freshwater lakes, reservoirs, ponds, etc. These water bodies play a decisive role in the survival and reproduction of human beings and other organisms as well as economic and social development (Dudgeon *et al.* 2006; Krivtsov *et al.* 2022). Due to their dissolubility and stability, the mobilization of PFASs from various origins into freshwater ecosystems occurs frequently, facilitating their accumulation within these aquatic environments.

PFASs have been reported in sediments, water, and biota at ng/g, ng/L, and μg/L levels, respectively (Ng *et al.* 2022; Suski *et al.* 2023). Tang *et al.* analyzed 35 types of legacy and emerging PFASs in the Poyang Lake revealing concentrations ranging from 23 to 1,000 ng/L in water and 0.26–2.9 ng/g dry weight in sediments, with short-chain and emerging PFASs such as perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS) (Tang *et al.* 2022). Industrial facilities are major point sources of the emission of PFASs to freshwater. Xu *et al.* evaluated PFAS environmental risks in a constructed wetland fed by industrial tailwater, and their findings suggested that with the accumulation and continued importation of PFASs, the risks remained notably substantial (Xu *et al.* 2022). Humans are widely exposed to PFASs through the consumption of aquatic food and drinking water, and researchers have reported thyroid, liver, and kidney diseases as well as metabolic dysfunction are related to PFAS exposure (Zeng *et al.* 2019).

A comprehensive understanding of PFAS transport and migration in freshwater systems is essential for assessing ecotoxicological risk and developing remediation strategies, ensuring the long-term viability of water resources, and contributing to the development of water management practices that prioritize sustainability, energy efficiency, and environmental responsibility (Raihan *et al.* 2023). While previous research has investigated transport behavior and reaction models for specific PFASs such as PFOA and PFOS (Jahn *et al.* 2023), it is essential to recognize that diverse types of PFASs exhibit distinct physicochemical properties (Wanzek *et al.* 2023), and the transport behaviors vary across different media environments. A comprehensive summary of research progress on the transportation of PFASs in freshwater environments serves to enhance our understanding of current research frontiers and hotspots that are helpful to guide future research.

Scientometrics, established in 1969, employs quantitative approaches to research developments within scientific fields. Bibliometric analysis, as a comprehensive investigative approach, integrates scientific and statistical methods to conduct quantitative research on given information. Moreover, it enables the identification of the impact and progression of scientific research, advancements in specific fields, and prevailing growth trends (Moodley *et al.* 2015). CiteSpace software was introduced in 2003 to conduct data visualization analyses and exhibits flexibility by facilitating co-occurrence and co-citation analyses, along with the capability for keywords' clustering analysis (Chen 2004). In this study, CiteSpace software version 6.2.R6 was used to analyze research publications collected from the Web of Science (WoS) core database in the field of transportation of PFASs in freshwater.

2. METHODOLOGY

2.1. Data sources and processing

The WoS Core Collection was selected as the data source. WoS is the most comprehensive academic information resource covering a wide range of disciplines, including the most influential core academic journals in each research field. According to Bradford's Law, a few core journals reveal adequate information to reflect achievements and progress in science (Brookes 1969). The searching keywords of WoS were set as follows: TS = (PFAS* OR *fluoroalkyl substances OR perfluorinated compounds) AND TS = (transport OR migration) AND TS = (aquatic OR freshwater OR wastewater OR inlandwater OR river* OR lake OR creek OR sewage OR estuary OR pond* OR reservoir OR stream OR runoff). The data range included all years and as of 2023.11.02, 433 publications had been searched out while meeting abstract, correction, book chapters and proceeding papers were excluded (Chen *et al.* 2023; Wang *et al.* 2023). After filtering out duplicate and unrelated publications, 306 papers were obtained. Combining the publications, 43 papers focused on the risks of PFASs in fresh water to humans and freshwater organisms. A total of 40 papers were based on the overall environment, including the aquatic environment, water bodies or the environment.

2.2. Scientometric analysis methods

CiteSpace is a Java-based tool for analyzing and visualizing co-citation and co-word networks. The analysis principle of the CiteSpace software is based on four theories. The structure of scientific revolutions provides CiteSpace with a philosophical basis; the theory of structure holes is embodied in CiteSpace to find nodes with a high degree of mediated centrality; CiteSpace also draws on the theory of optimal information foraging and the algorithm for detecting sudden increase in frequency for better literature analysis (Chen 2004). CiteSpace 6.2.R6 was used to conduct the scientometric analysis in the study. The time slice was set to one year, and the node types were selected as country, institution, and keywords. The scale factor k of the g-index was set as 25. Finally, Figure 1 was illustrated in Origin 2023 and Figures 2–5 were created by using CiteSpace.

3. RESULTS AND DISCUSSION

3.1. Publications' growth trends

The trends of publications and the sum of total citations per year (SOTC) are shown in Figure 1. The studies related to the transportation of PFASs in freshwater started late with the first publication in 2005. This study delineated perfluorinated chemical (PFC) concentrations in surface water, contending that the primary source is non-atmospheric in Lake Michigan, and the most probable source was identified as discharges from wastewater treatment (Simcik & Dorweiler 2005). The number of works grew at a relatively low rate during 2005–2014. Researchers paid attention to occurrences and distribution of PFASs in aquatic environments or adsorption behaviors and mechanisms (Du *et al.* 2014) of PFASs in various absorbents in this stage. The regulatory framework for assessing PFASs in water was established by the United States Environmental Protection Agency (U.S. EPA). Specifically, the analytical methodology designated as Method 537.1, as promulgated by the U.S. EPA, was implemented for the comprehensive detection of 26 distinct PFAS compounds in water samples (Sharma *et al.* 2016). However, knowledge gaps remained in the transport and removal mechanisms of PFASs.

The publication rate of literature accelerated during 2015–2023. Differing from the embryonic stage, in this period, researchers have focused on the transformation and toxicity of PFASs in water environments. More detection standards for PFASs in water environments have been introduced successively, and these standards have broadened the detecting ranges of types of PFASs and samples (Lipps *et al.* 2021). As the study developed

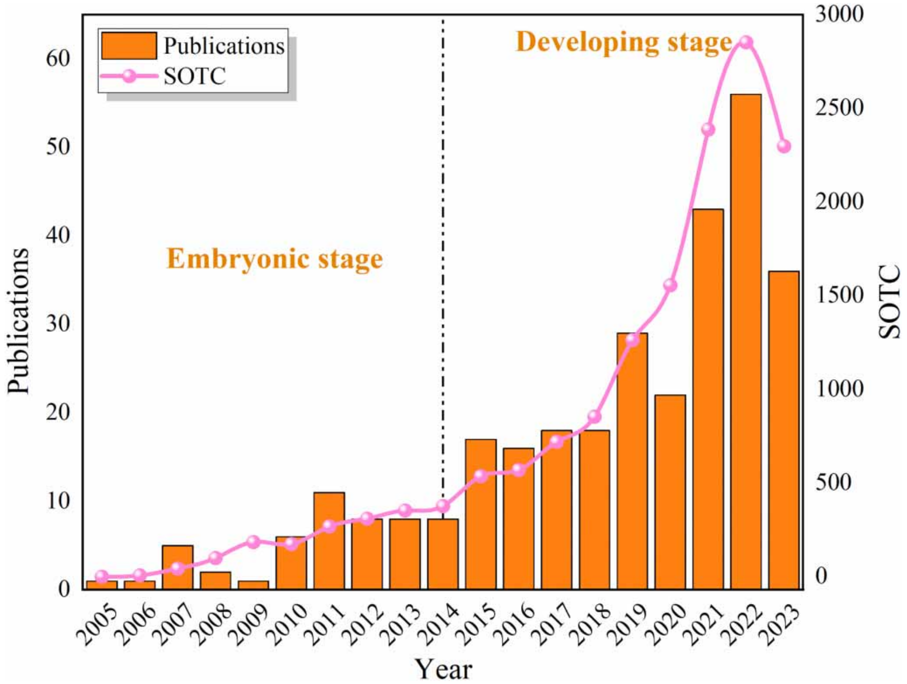


Figure 1 | Annual publications and SOTC from 2005 to 2023.

in-depth, remediation technologies of PFASs (Kucharzyk *et al.* 2017), as well as the discussion on risks to human health and aquatic ecosystems (Sims *et al.* 2022), were increasingly becoming prominent.

3.2. Cooperation network analysis

The national collaboration, institutional and co-authorship networks were employed to assess the influential academic groups and collaborative dynamics related to the transportation of PFASs in freshwater. This analysis aimed to elucidate the interconnected relationships among research groups in the specified field. The cooperation network of the country/region, global institutes and authors are shown in Figure 2, and the details of the network analysis are listed in Tables 1–3.

3.2.1. Country/region cooperation analysis

Our investigation revealed that 42 distinct countries or regions undertook research endeavors concerning the transportation of PFASs in freshwater environments (Figure 2(a) and Table 1). Notably, China (120), the United States (97), Canada (39), Germany (20), and Sweden (19) emerged as the predominant contributors, constituting the top quintile of nations in this domain. The number of publications associated with transportation of PFASs in freshwater demonstrates a substantial asymmetry, with China and the United States displaying significantly elevated levels compared with their counterparts. This pattern indicated the heightened interest and engagement of Chinese and American researchers, underscoring an escalating awareness of PFAS-related challenges within both nations. The United States occupied a preeminent central position within this research domain, possessing a betweenness centrality value of 0.58. Subsequent in rank are China (0.35), Netherlands (0.27), Sweden (0.18), and England (0.15). These metrics signify the pivotal roles played by these countries or regions in facilitating international collaborative initiatives within the research milieu of transportation of PFASs in freshwater.

3.2.2. Institution cooperation analysis

In total, 205 institutions researched in the field of transportation of PFASs in freshwater (Figure 2(b) and Table 2). Our analysis revealed the pivotal role of Chinese research institutions in the study of transportation of PFASs in freshwater. Specifically, the Chinese Academy of Sciences (Chinese Acad Sci) emerged as a key contributor, demonstrating significance through both a higher publication count (54) and a substantial betweenness centrality of 0.36. Despite a relatively recent initiation of research activities in transportation of PFASs in freshwater by the Chinese Academy of Sciences in 2010, its rapid development propelled it to a leading position in the field.

Figure 2 | Cooperation networks of (a) countries/regions, (b) institutions, and (c) co-authorship. Within the network, betweenness centrality serves as a metric for discerning the significance of individual nodes, wherein higher values denote a greater overarching influence of key nodes. The strength of collaborations is represented by the width of lines connecting nodes.

Moreover, the collaborative landscape among Chinese institutions appeared robust. Notably, the Academy of Sciences engages in collaborative research with institutions such as the University of Chinese Academy of Sciences, the Research Center for Eco-environmental Sciences, Hohai University, and the Guangzhou Institute of Geochemistry. These collaborative efforts underscored the institution's active involvement and leadership in fostering cooperative research initiatives within the broader scientific community. Moreover, as the largest research institution in Germany, the Helmholtz Association held a high betweenness centrality of 0.11, and it mainly contributed to the field of transportation of PFASs in freshwater between 2010 and 2015. Environment & Climate Change Canada and US EPA though had a relatively small number of publications, holding high betweenness centrality of 0.09 and 0.08, respectively.

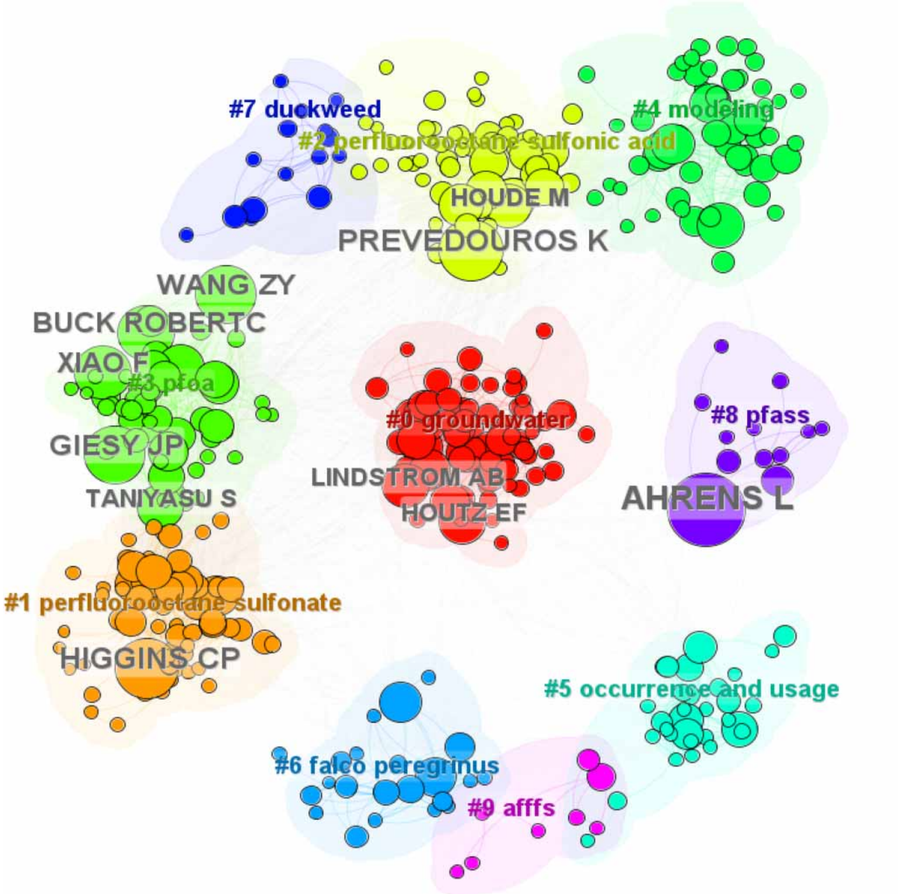


Figure 3 | Co-citation clustering network. The number of clusters represents the co-citation strength of scholars related to the topic.

3.2.3. Author cooperation analysis

The core of the author cooperation analysis network is represented in Figure 2(c) and Table 3. Researchers had close cooperation in this field of transportation of PFASs in freshwater. The corporation network was divided into two parts. The right part is larger, and it included Wang and Wang. The team group was led by Wang and they had close collaborations with each other in the field of sources, multimedia distributions, and health risk assessments of PFASs in China. The left team group was led by Ahrens, Lutz and included Lam and Ebinghaus. Their studies focused on the PFASs' fate, effects, and removal technologies in water environments. Giesy and Zhao had collaborations with both team groups.

Although the authors from China started late in the field, they showed great ability to publish. Among all authors, Wang published most papers, at 13. After reviewing all his papers, we found he had close collaboration with Lu, Yonglong whose research team unveiled the occurrence and transportation of perfluoroalkyl acids (PFAA) in the coastal rivers of South Bohai, where fluoropolymer facilities were concentrated (Wang *et al.* 2014). The research career of Ahrens, Lutz in the topic related to transportation of PFASs in freshwater was the longest among nine authors. He started his research in the field with studying the distribution of PFCs in fish livers from alpine lakes (Ahrens *et al.* 2010). In recent years, his team has focused on the transportation in water and the pollution to drinking water by sampling in different media (Nguyen *et al.* 2022).

3.3. Co-citation clustering analysis

Using co-citation clustering analysis, we identify whose publications were highly cited and valued related to the field of transportation of PFASs in freshwater (Figure 3). A larger number of clusters suggest a more diverse and fragmented landscape of research within the topic. A fewer clusters imply a more focused and concentrated area of research. Lindstrom and Houtz were in the strongest cluster '#0 groundwater', and Higgins was in the cluster '#1 perfluorooctane sulfonate'. The number of representative scholars in cluster '#2 pfoa' was the most with

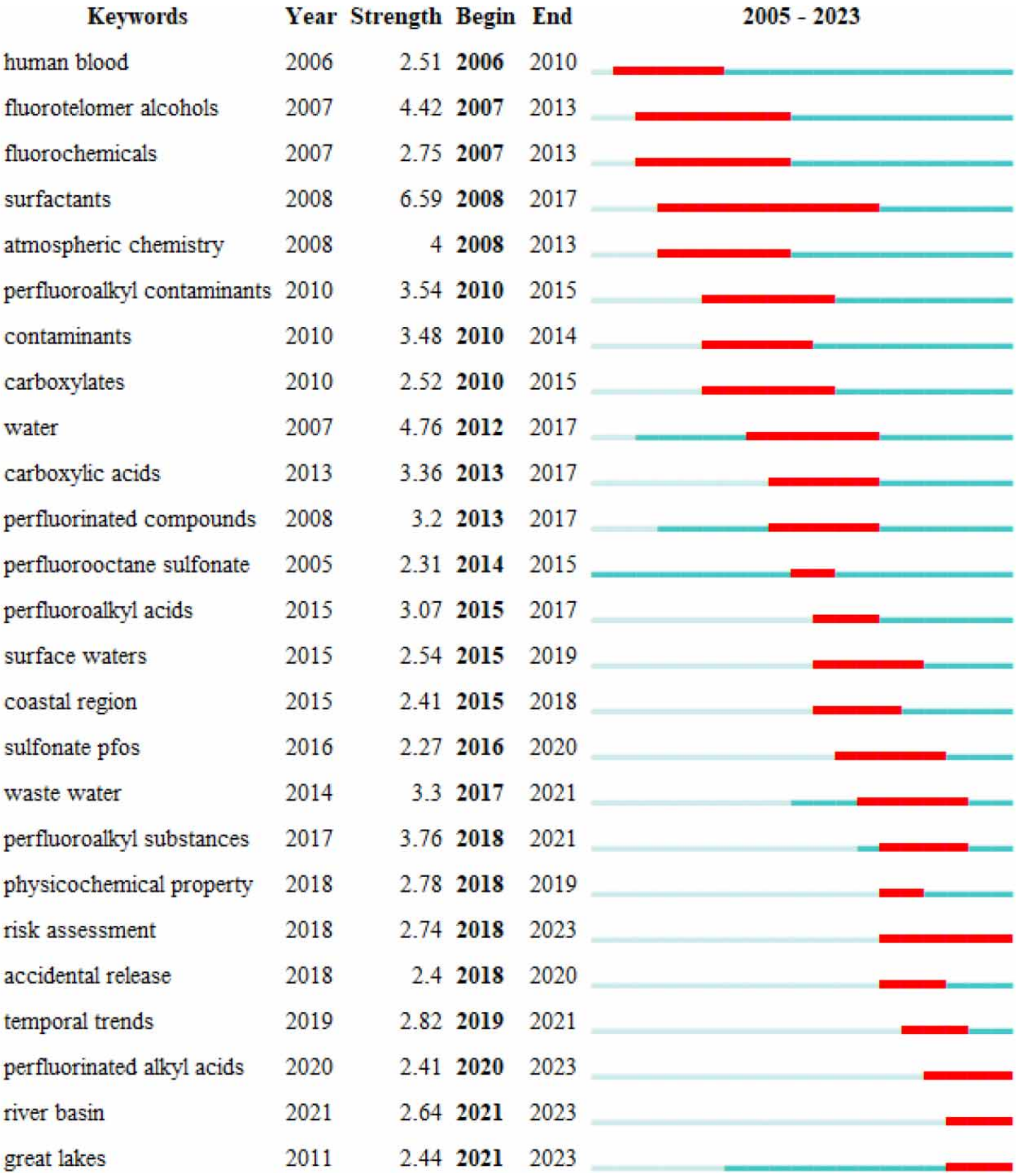


Figure 4 | Keywords with the strongest occurrence burst on the transportation of PFASs in freshwater. Instances where the keyword or article has not yet emerged or been published are represented by light blue lines, while the initial appearance or publication date is indicated by dark blue lines. The commencement of a red line signifies the start of a burst period, concluding at its endpoint to denote its termination.

Wang, Buck, Xiao, Giesy, and Taniyasu. Meanwhile, Prevedouros and Houde were in '#2 perfluorooctane sulfonic acid', and Ahrens was included in '#8 pfass'. The rest of the clusters received varying degrees of attention, none of them had representative researchers.

3.4. Progress of research topics and trends

3.4.1. Keywords' bursting analysis

The keywords' bursting analysis is shown in Figure 4. The keyword 'surfactants' demonstrated more considerable prominence during the extended timeframe spanning from 2008 to 2017. Due to their high surface activity, thermal stability, and chemical stability, PFASs were used as surfactants and widely applied in producing non-stick pan coating, water-resistant clothing, and greaseproof food packaging, etc. (Kucharzyk *et al.* 2017). Owing to the

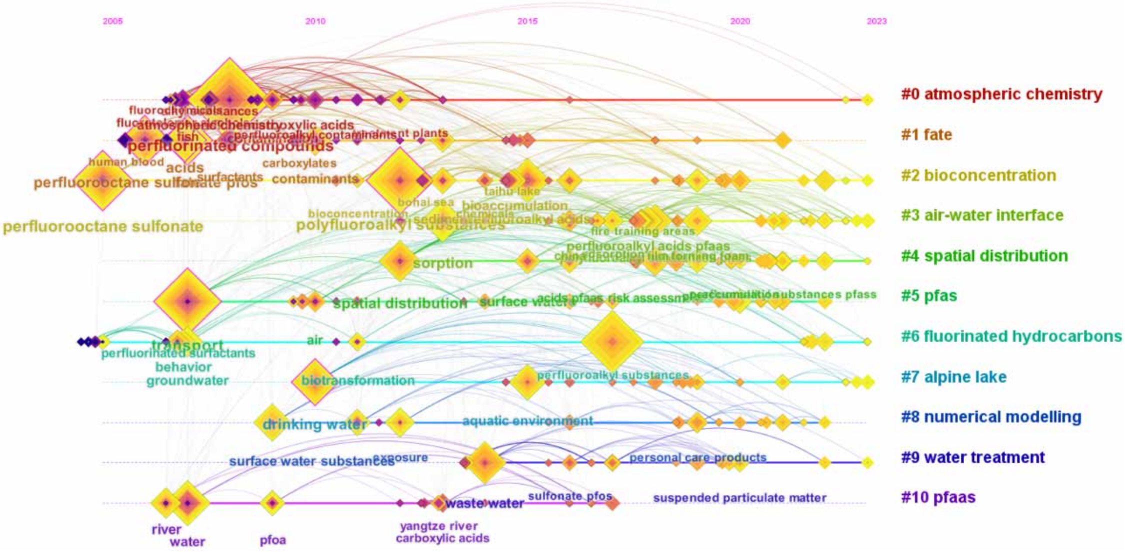


Figure 5 | Clustering timeline map of keywords. The larger the size of a keyword node, the more attention it receives.

Table 1 | Indexes of the cooperation networks of the top 10 most productive countries/regions

Rank	Countries/Regions	Count	Ratio (%)	Centrality
1	China	120	39.22	0.35
2	USA	97	31.70	0.58
3	Canada	39	12.75	0.14
4	Germany	20	6.54	0.10
5	Sweden	19	6.21	0.18
6	South Korea	12	3.92	0.00
7	Australia	12	3.92	0.09
8	England	11	3.59	0.15
9	Italy	10	3.27	0.08
10	Norway	10	3.27	0.02

Table 2 | Indexes of the cooperation networks of the top 10 most productive institutions

Rank	Institutions	Countries/Regions	Count	Ratio (%)	Centrality
1	Chinese Acad Sci	China	50	16.34	0.28
2	Univ Chinese Acad Sci	China	31	10.13	0.04
3	Res Ctr Ecoenvironm Sci	China	28	9.15	0.02
4	Helmholtz Association	Germany	15	4.90	0.11
5	Environ & Climate Change Canada	Canada	15	4.90	0.09
6	City Univ Hong Kong	China	11	3.59	0.07
7	US EPA	USA	10	3.27	0.08
8	Hohai Univ	China	10	3.27	0.01
9	Chinese Res Inst Environm Sci	China	9	2.94	0.03
10	Helmholtz Zentrum Geesthacht	Germany	9	2.94	0.01

Table 3 | Indexes of the cooperation networks of authors with more than five publications

Rank	Authors	Countries/Regions	Count	Ratio (%)	Centrality
1	Wang	China	13	4.25	0.01
2	Lu	China	12	3.92	0.01
3	Ahrens	Germany	11	3.59	0.06
4	Giesy	Canada	8	2.61	0.04
5	Li	China	7	2.29	0.00
6	Wang	China	7	2.29	0.00
7	Ebinghaus	Germany	6	1.96	0.06
8	Zhao	China	6	1.96	0.01
9	Lam	China	6	1.96	0.05

robust C–F bonds they possess and the presence of hydrophilic functional groups, PFASs exhibit a propensity to readily dissolve and persist for a long time in aquatic environments. Thus, PFASs were widely identified across diverse environmental matrices of freshwater. Zhou *et al.* detected PFASs in water, sediment, and biological samples collected near a fluorochemical industrial base (Zhou *et al.* 2013). Concerning the persistent presence of PFASs in freshwater arising from surfactant production over an extended period, the European Chemicals Agency (ECHA) has put forth a proposal for the prohibition of PFASs (Wollin *et al.* 2023).

In the initial period, researchers mainly focused on the wide presence and transport behaviors of PFASs and their precursors such as fluorotelomer alcohols in the environment (Wang *et al.* 2015). The occurrence of PFASs in human bodies was mainly determined by measuring the concentration in human blood. The burstiness of 'human blood' in 2006–2010 indicated that researchers realized bioconcentration of PFASs in the human body, while the specific mechanisms of bioconcentration and toxicity of PFASs were not clear at the time (Fujii *et al.* 2007). PFASs contain a hydrophilic functional head commonly carboxylic or sulfonic acid. Hence, PFASs commonly include two types: perfluorocarboxylic acids (PFCA) and perfluorosulfonic acids (PFSA). The keyword 'atmospheric chemistry' demonstrated strong strength of 4 between 2008 and 2013. Cai *et al.* investigated spatial distribution and the composition profiles of PFASs in Antarctica and concluded that atmospheric deposition was the main pollution source in lakes (Cai *et al.* 2012).

The keyword 'water' showed a strong strength of 4.76 between 2012 and 2017. Adsorption is the major transport process of contaminants in freshwater environments. Adsorption is not only efficient for the removal of PFASs from water but also influences the distribution of PFASs at interfaces and their fate in aquatic environments (Du *et al.* 2014). Adsorption mechanisms contain electrostatic interaction, hydrophobic interaction, ligand and ion exchange, and hydrogen bond, while electrostatic interaction and hydrophobic interaction have the greatest influence on the transport process. Due to hydrophobic C–F bonds, negatively charged PFASs can adsorb onto hydrophobic media surfaces (Deng *et al.* 2012), indicating that hydrophobic interaction could impede the transportation of PFASs, particularly for long-chain PFASs with more C–F bonds. Due to hydrophilic functional head of PFASs, anionic PFASs are the majority in the adsorption process. Electrostatic attraction, electrostatic repulsion, and divalent metal cation bridging effect can affect adsorptions between anionic PFASs and charged media surfaces. PFASs with longer chains are less affected by electrostatic interaction, owing to their longer molecular stretching distance (Li *et al.* 2023).

With the basic adsorption mechanism of PFASs being clearer, researchers began to focus on topics in 'surface waters' and 'waste water'. As for 'waste water', it is mainly associated with WWTPs as a point source of PFASs and its removal technologies (Banks *et al.* 2020). With the development of mathematical simulation, the experimental methods on physicochemical properties of PFASs are essential to reduce uncertainties of transport, transform, and fate simulation (Liu *et al.* 2019). Owing to the extensive data accumulated through long-term PFASs monitoring, researchers have been able to investigate the temporal trends of PFASs in freshwater transportation (Shi *et al.* 2021). In recent years, research related to 'risk assessment', 'perfluorinated alkyl acids', 'great lakes', and 'river basin' have been bursting. Aquatic biota are widely exposed to PFASs in freshwater, and human consumption of aquatic food leads to the bioaccumulation of PFASs in the body. Thus, exposure risks of PFASs to environments and human health need to be urgently assessed (Kurwadkar *et al.* 2022). The

Great Lakes is of great importance as this large freshwater system provides drinking water and aquatic food to millions of people. Researchers highlighted PFASs source apportionment (Lin *et al.* 2021), accumulation, and toxicity (Bartlett *et al.* 2021) to aquatic organisms in the Great Lakes. The river basin contains almost all types of freshwater bodies. Nevertheless, most studies on PFASs in environments focused on a single type of environment medium or a combination of two. There is a scarcity of research that explores PFASs across various environment media simultaneously (Liu *et al.* 2022).

3.4.2. Keywords timeline analysis

The timeline analysis of keywords in different clusters is shown in Figure 5. The cluster '#2 bioconcentration' was highlighted at the beginning. Researchers detected the bioconcentration of PFASs in various aquatic organisms (Conder *et al.* 2008). Later in 2006–2008, '#0 atmospheric chemistry', '#1 fate', '#5 pfas', and '#10 pfaas' were emphasized. In this period, owing to knowledge gaps in PFASs' fate in freshwater, researchers focused on the environmental factors affecting PFASs' fate rather than fate itself (Johnson *et al.* 2007). Due to their biotoxicity, environmental persistence, and bioaccumulation (Li *et al.* 2023), it is essential to reduce the use of PFASs and evaluate their transportation and transformation in freshwater environment matrices (Podder *et al.* 2021). Additionally, as a prevalent type of PFASs, PFAA gradually attracted considerable attention. '#0 atmospheric chemistry' was related to the global distribution of PFASs. Pfotenhauer *et al.* revealed that wet deposition was an important supplement with PFASs in freshwater (Pfotenhauer *et al.* 2022). The cluster '#7 alpine lake' was a hotspot along with '#1 fate' in 2010. The occurrence of PFASs in remote areas such as alpine lakes indicated the importance of atmosphere transportation (Taniyasu *et al.* 2013).

Noteworthily, '#2 bioconcentration' has been highlighted again since 2012. Differing from the previous period, researchers made significant contributions to deepening our understanding of the toxicity of PFASs in organisms (Zhang & Lerner 2012). Meanwhile, '#3 air-water interface' and '#4 spatial distribution' were hotspots at this period. The transfer processes between phases comprise a key factor influencing the transportation and fate of PFASs. Meanwhile, considering the molecular characteristics of PFASs, it is compulsory to also consider adsorption at the air-water interface as a potential retention mechanism influencing spatial distribution in environmental systems (Brusseau 2019). The cluster '#6 fluorinated hydrocarbons' was emphasized in 2017. As a precursor of PFASs, fluorinated hydrocarbons (HFC) can form PFASs through atmospheric degradation, and PFASs were detected in the Arctic ice cap (Hartz *et al.* 2023).

It's noteworthy that '#8 numerical modeling' appeared in 2009 and 2014. Numerical models were widely used to simulate transportation of PFASs in freshwater since relatively higher costs in terms of both labor and time (Wang *et al.* 2016). These numerical models were largely process-based, utilizing established theories for their formulation. Recently, integrated models have been set up to simulate PFASs' fate and transportation in a large basin (Raschke *et al.* 2022). Integrated models are efficient for PFASs' transport due to their accuracy and capacity to couple environment metrices together. Additionally, '#9 water treatment' also appeared in 2009 and 2014, suggesting that wastewater and drinking water treatments are essential to remove PFASs from water. Currently, the main removal and degradation technologies include electrochemical degradation, enzymatic transformation, advanced oxidation, and photocatalytic degradation (Araujo *et al.* 2022).

3.5. Limitations

This research has several limitations: (1) Single data source. This research only set the WoS core Collection as the database. Not all literature works in the field of transportation of PFASs in freshwater are included in WoS, meaning that we could not make a comprehensive analysis of all relevant literature. (2) Insufficient performance of CiteSpace. The CiteSpace software cannot induct synonyms, resulting in 'PFAA' and 'perfluorinated alkyl acids' occurring in keywords bursting analysis while they exhibit semantic equivalence. Meanwhile, CiteSpace could not determine orders of authors so that we could not distinguish their interrelationships. (3) Due to the scope of the study, specific transportation equations were not discussed in this research.

4. CHALLENGES AND OPPORTUNITIES

One significant challenge is the co-occurrence of PFASs with other contaminants, specifically microplastics (MPs). An in-depth exploration of how the presence of MPs may interact with PFASs is needed, elucidating the mechanisms governing their interaction and the potential combined toxicity (Dai *et al.* 2022). Moreover, hydrological factors, such as water pulse change, ecological water supplementation, and occurrences of intense rainfall and floods, have been recognized as influential determinants in the distribution and transportation of contaminants in freshwater ecosystems. An expanded research focus is warranted to comprehensively investigate the impact of hydrological factors on PFASs' transport, distribution, and associated ecological implications.

Integrated large-scale modeling is a trend for exploring transportation of PFASs. This involves the incorporation of diverse factors, such as hydrological, environmental, and geographical parameters into a unified model, which contribute to a more holistic understanding of transportation of PFASs in freshwater environments (Raschke *et al.* 2022). Meanwhile, future investigations should delve into developing and implementing sustainable strategies for mitigating PFASs in freshwater, acknowledging the imperatives of energy efficiency and environmental responsibility (Xu *et al.* 2022).

5. CONCLUSIONS

This research conducted a bibliometric analysis related to the transportation of PFASs in freshwater. We analyzed publications growth trends and cooperations among countries/regions, institutions, and authors. It is noteworthy that the progress of research topics and trends in this field was emphasized in this study. The growth of publications went through two stages: the 'embryonic' stage (2005–2014) and the 'developing' stage (2015–2023). In terms of cooperations analysis, although Chinese scholars started research related to the topic late, China has played a leading role since then. According to keywords' analysis of burstiness and timeline, we traced the development of this research field. Moreover, the current research exhibits a shift from the transportation of specific PFASs in single or dual media to a broader spectrum of the transportation of PFASs across multiple media. Current research has unveiled an expanded understanding of the mechanisms and properties governing the transportation of PFASs in freshwater, surpassing previous knowledge. Joint efforts are recommended in the future to delve into the transportation of PFASs in multimedia and facilitate technological innovation while persistently mitigating the sources of PFASs.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Ahrens, L., Marusczak, N., Rubarth, J., Dommergue, A., Nedjai, R., Ferrari, C. & Ebinghaus, R. 2010 Distribution of perfluoroalkyl compounds and mercury in fish liver from high-mountain lakes in France originating from atmospheric deposition. *Environ. Chem.* **7** (5), 422–428. https://doi.org/10.1071/EN10025.

Araujo, R., Rodriguez-Hernandez, J., Gonzalez-Gonzalez, R., Macias-Garbett, R., Martinez-Ruiz, M., Reyes-Pardo, H., Martinez, S., Parra-Arroyo, L., Melchor-Martinez, E., Sosa-Hernandez, J., Coronado-Apodaca, K., Varjani, S., Barcelo, D., Iqbal, H. & Parra-Saldivar, R. 2022 Detection and tertiary treatment technologies of poly-and perfluoroalkyl substances in wastewater treatment plants. *Front. Env. Sci-Switz.* **10**. https://doi.org/10.3389/fenvs.2022.864894.

Banks, D., Jun, B., Heo, J., Her, N., Park, C. & Yoon, Y. 2020 Selected advanced water treatment technologies for perfluoroalkyl and polyfluoroalkyl substances: A review. *Sep. Purif. Technol.* **231**. https://doi.org/10.1016/j.seppur.2019.115929.

Bartlett, A., De Silva, A., Schissler, D., Hedges, A., Brown, L., Shires, K., Miller, J., Sullivan, C., Spencer, C. & Parrott, J. 2021 Lethal and sublethal toxicity of perfluorooctanoic acid (PFOA) in chronic tests with Hyalella azteca (amphipod) and early-life stage tests with Pimephales promelas (fathead minnow). *Ecotox. Environ. Safe.* **207**. https://doi.org/10.1016/j.ecoenv.2020.111250.

Brookes, B. 1969 Bradfords law and bibliography of science. *Nature.* **224** (5223), 953. https://doi.org/10.1038/224953a0.

Brusseau, M. 2019 The influence of molecular structure on the adsorption of PFAS to fluid-fluid interfaces: using QSPR to predict interfacial adsorption coefficients. *Water. Res.* **152**, 148–158. https://doi.org/10.1016/j.watres.2018.12.057.

Cai, M., Yang, H., Xie, Z., Zhao, Z., Wang, F., Lu, Z., Sturm, R. & Ebinghaus, R. 2012 Per- and polyfluoroalkyl substances in snow, lake, surface runoff water and coastal seawater in Fildes Peninsula, King George Island, Antarctica. *J. Hazard. Mater.* **209**, 335–342. https://doi.org/10.1016/j.jhazmat.2012.01.030.

Chen, C. 2004 Searching for intellectual turning points: Progressive knowledge domain visualization. *P. Natl. Acad. Sci. Usa.* **101**, 5303–5310. https://doi.org/10.1073/pnas.0307513100.

Chen, G., Bai, J., Bi, C., Wang, Y. & Cui, B. 2023 Global greenhouse gas emissions from aquaculture: A bibliometric analysis. *Agriculture, Ecosystems & Environment* **348**, 108405. https://doi.org/10.1016/j.agee.2023.108405.

Conder, J., Hoke, R., De Wolf, W., Russell, M. & Buck, R. 2008 Are PFCAs bioaccumulative? A critical review and comparison with regulatory lipophilic compounds. *Environ. Sci. Technol.* **42** (4), 995–1003. https://doi.org/10.1021/es070895g.

Dai, Y., Zhao, J., Sun, C., Li, D., Liu, X., Wang, Z., Yue, T. & Xing, B. 2022 Interaction and combined toxicity of microplastics and per- and polyfluoroalkyl substances in aquatic environment. *Frontiers of Environmental Science & Engineering* **16** (10). https://doi.org/10.1007/s11783-022-1571-2.

Dasu, K., Xia, X., Siriwardena, D., Klupinski, T. P. & Seay, B. 2022 Concentration profiles of per- and polyfluoroalkyl substances in major sources to the environment. *J. Environ. Manag.* **301** (113879). https://doi.org/10.1016/j.scitotenv.2023.164052.

Deng, S., Zhang, Q., Nie, Y., Wei, H., Wang, B., Huang, J., Yu, G. & Xing, B. 2012 Sorption mechanisms of perfluorinated compounds on carbon nanotubes. *Environ. Pollut.* **168**, 138–144. https://doi.org/10.1016/j.envpol.2012.03.048.

Du, Z., Deng, S., Bei, Y., Huang, Q., Wang, B., Huang, J. & Yu, G. 2014 Adsorption behavior and mechanism of perfluorinated compounds on various adsorbents-A review. *J. Hazard. Mater.* **274**, 443–454. https://doi.org/10.1016/j.jhazmat.2014.04.038.

Dudgeon, D., Arthington, A., Gessner, M., Kawabata, Z., Knowler, D., Lévéque, C., Naiman, R., Prieur-Richard, A., Soto, D., Stiassny, M. & Sullivan, C. 2006 Freshwater biodiversity: Importance, threats, status and conservation challenges. *Biol. Rev.* **81** (2), 163–182. https://doi.org/10.1017/S1464793105006950.

Fujii, S., Polprasert, C., Tanaka, S., Lien, N. & Qiu, Y. 2007 New POPs in the water environment: Distribution, bioaccumulation and treatment of perfluorinated compounds – A review paper. *J. Water. Supply. Res. T.* **56** (5), 313–326. https://doi.org/10.2166/aqua.2007.005.

Hartz, W., Björnsdotter, M., Yeung, L., Hodson, A., Thomas, E., Humby, J., Day, C., Jogsten, I., Kärrman, A. & Kallenborn, R. 2023 Levels and distribution profiles of Per- and Polyfluoroalkyl Substances (PFAS) in a high Arctic Svalbard ice core. *Sci. Total. Environ.* **871**. https://doi.org/10.1016/j.scitotenv.2023.161830.

Jahn, K., Saffer, D., Freeman, K. & Lincoln, S. 2023 Storage, transport, and fate of perfluoroalkyl acids (PFAAs) in a wastewater reuse and groundwater recharge system. *Water. Resour. Res.* **59** (9). https://doi.org/10.1029/2022WR034321.

Johnson, R., Anschutz, A., Smolen, J., Simcik, M. & Penn, R. 2007 The adsorption of perfluorooctane sulfonate onto sand, clay, and iron oxide surfaces. *J. Chem. Eng. Data.* **52** (4), 1165–1170. https://doi.org/10.1021/je060285g.

Krivtsov, V., Forbes, H., Birkinshaw, S., Olive, V., Chamberlain, D., Buckman, J., Yahr, R., Arthur, S., Christie, D., Monteiro, Y. & Diekonigin, C. 2022 Ecosystem services provided by urban ponds and green spaces: A detailed study of a semi-natural site with global importance for research. *Blue-Green Systems* **4** (1), 1–23. https://doi.org/10.2166/bgs.2022.021.

Kucharzyk, K., Darlington, R., Benotti, M., Deeb, R. & Hawley, E. 2017 Novel treatment technologies for PFAS compounds: A critical review. *J. Environ. Manage.* **204**, 757–764. https://doi.org/10.1016/j.jenvman.2017.08.016.

Kurwadkar, S., Dane, J., Kanel, S., Nadagouda, M., Cawdrey, R., Ambade, B., Struckhoff, G. & Wilkin, R. 2022 Per- and polyfluoroalkyl substances in water and wastewater: A critical review of their global occurrence and distribution. *Sci. Total. Environ.* **809**. https://doi.org/10.1016/j.scitotenv.2021.151003.

Li, H., Dong, Q., Zhang, M., Gong, T., Zan, R. & Wang, W. 2023 Transport behavior difference and transport model of long- and short-chain per- and polyfluoroalkyl substances in underground environmental media: A review. *Environ. Pollut.* **327**. https://doi.org/10.1016/j.envpol.2023.121579.

Lin, Y., Capozzi, S., Lin, L. & Rodenburg, L. 2021 Source apportionment of perfluoroalkyl substances in Great Lakes fish. *Environ. Pollut.* **290**. https://doi.org/10.1016/j.envpol.2021.118047.

Lipps, W., Prakash, B. & Schug, K. 2021 A review of ASTM d7979 for the analysis of per- and polyfluorinated alkyl substances in non-potable water by co-solvation with methanol and using liquid chromatography-tandem mass spectrometry. *J. Sep. Sci.* **44** (11), 2234–2249. https://doi.org/10.1002/jssc.202000858.

Liu, W., Wu, J., He, W. & Xu, F. 2019 A review on perfluoroalkyl acids studies: Environmental behaviors, toxic effects, and ecological and health risks. *Ecosyst. Health. Sust.* **5** (1). https://doi.org/10.1080/20964129.2018.1558031.

Liu, Z., Zhou, J., Xu, Y., Lu, J., Chen, J. & Wang, J. 2022 Distributions and sources of traditional and emerging per- and polyfluoroalkyl substances among multiple environmental media in the Qiantang River watershed, China. *Rsc. Advances.* **12** (33), 21247–21254. https://doi.org/10.1039/d2ra02385g.

Moodley, J., Singh, V., Kagina, B., Abdullahi, L. & Hussey, G. 2015 A bibliometric analysis of cancer research in South Africa: Study protocol. *Bmj. Open.* **5** (2). https://doi.org/10.1136/bmjopen-2014-006913.

Ng, K., Alygizakis, N., Androulakakis, A., Galani, A., Aalizadeh, R., Thomaidis, N. & Slobodnik, J. 2022 Target and suspect screening of 4777 per- and polyfluoroalkyl substances (PFAS) in river water, wastewater, groundwater and biota samples in the Danube River Basin. *J. Hazard. Mater.* **436**. https://doi.org/10.1016/j.jhazmat.2022.129276.

Nguyen, M., Norström, K., Wiberg, K., Gustavsson, J., Josefsson, S. & Ahrens, L. 2022 Seasonal trends of per- and polyfluoroalkyl substances in river water affected by fire training sites and wastewater treatment plants. *Chemosphere.* **308**. https://doi.org/10.1016/j.chemosphere.2022.136467.

Pfotenhauer, D., Sellers, E., Olson, M., Praedel, K. & Shafer, M. 2022 PFAS concentrations and deposition in precipitation: an intensive 5-month study at national atmospheric deposition program – national trends sites (NADP-NTN) across Wisconsin, USA. *Atmos. Environ.* **291**. https://doi.org/10.1016/j.atmosenv.2022.119368.

Podder, A., Panja, S., Chaudhuri, A., Roy, A., Biswas, M. & Homechaudhuri, S. 2021 Role of morphology in shaping the feeding niche of fishes inhabiting Eastern Himalayan torrential rivers of West Bengal, India. *Ecol. Freshw. Fish.* **30** (4), 444–465. https://doi.org/10.1111/eff.12596.

Raihan, A., Pereira, J. J., Begum, R. A. & Rasiah, R. 2023 The economic impact of water supply disruption from the selangor river. *Malaysia. Blue-Green Systems* **5** (2), 102–120. https://doi.org/10.2166/bgs.2023.031.

Raschke, A., Nejadhashemi, A. & Rafiei, V. 2022 Overview of modeling, applications, and knowledge gaps for integrated large-Scale PFAS modeling. *J. Environ. Eng.* **148** (9). https://doi.org/10.1061/(ASCE)EE.1943-7870.0002033.

Sharma, B. M., Bharat, G. K., Tayal, S., Larssen, T., Bečanová, J., Karásková, P., Whitehead, P. G., Futter, M. N., Butterfield, D. & Nizzetto, L. 2016 Perfluoroalkyl substances (PFAS) in river and ground/drinking water of the Ganges River basin: Emissions and implications for human exposure. *Environ. Pollut.* **208**, 704–713. https://doi.org/10.1016/j.envpol.2015.10.050.

Shi, B., Wang, T., Yang, H., Zhou, Y., Bi, R., Yang, L., Yoon, S., Kim, T. & Khim, J. 2021 Perfluoroalkyl acids in rapidly developing coastal areas of China and South Korea: Spatiotemporal variation and source apportionment. *Sci. Total. Environ.* **761**. https://doi.org/10.1016/j.scitotenv.2020.143297.

Simcik, M. & Dorweiler, K. 2005 Ratio of perfluorochemical concentrations as a tracer of atmospheric deposition to surface waters. *Environ. Sci. Technol.* **39** (22), 8678–8683. https://doi.org/10.1021/es0511218.

Sims, J., Stroski, K., Kim, S., Killeen, G., Ehalt, R., Simcik, M. & Brooks, B. 2022 Global occurrence and probabilistic environmental health hazard assessment of per- and polyfluoroalkyl substances (PFASs) in groundwater and surface waters. *Sci. Total. Environ.* **816**. https://doi.org/10.1016/j.scitotenv.2021.151535.

Suski, J., Chanov, M., Heron, C., Field, J. & Salice, C. 2023 Ecotoxicity and accumulation of perfluorononanoic acid in the fathead minnow (Pimephales promelas) and an approach to developing protective thresholds in the aquatic environment through species sensitivity distribution. *Environ. Toxicol. Chem.* **42** (10), 2229–2236. https://doi.org/10.1002/etc.5692.

Tang, A., Zhang, X., Li, R., Tu, W., Guo, H., Zhang, Y., Li, Z., Liu, Y. & Mai, B. 2022 Spatiotemporal distribution, partitioning behavior and flux of per- and polyfluoroalkyl substances in surface water and sediment from Poyang Lake, China. *Chemosphere.* **295**. https://doi.org/10.1016/j.chemosphere.2022.133855.

Taniyasu, S., Yamashita, N., Moon, H., Kwok, K., Lam, P., Horii, Y., Petrick, G. & Kannan, K. 2013 Does wet precipitation represent local and regional atmospheric transportation by perfluorinated alkyl substances? *Environ. Int.* **55**, 25–32. https://doi.org/10.1016/j.envint.2013.02.005.

Wang, P., Lu, Y., Wang, T., Fu, Y., Zhu, Z., Liu, S., Xie, S., Xiao, Y. & Giesy, J. 2014 Occurrence and transport of 17 perfluoroalkyl acids in 12 coastal rivers in south Bohai coastal region of China with concentrated fluoropolymer facilities. *Environ. Pollut.* **190**, 115–122. https://doi.org/10.1016/j.envpol.2014.03.030.

Wang, C., Ruan, T., Liu, J., He, B., Zhou, Q. & Jiang, G. 2015 Perfluorooctyl iodide stimulates steroidogenesis in h295r cells via a cyclic adenosine monophosphate signaling pathway. *Chem. Res. Toxicol.* **28** (5), 848–854. https://doi.org/10.1021/tx5004563.

Wang, X., Zhang, J. & Babovic, V. 2016 Improving real-time forecasting of water quality indicators with combination of process-based models and data assimilation technique. *Ecol. Indic.* **66**, 428–439. https://doi.org/10.1016/j.ecolind.2016.02.016.

Wang, Y., Bai, J., Zhang, L., Liu, H., Wang, W., Liu, Z. & Zhang, G. 2023 Advances in studies on the plant rhizosphere microorganisms in wetlands: A visualization analysis based on CiteSpace. *Chemosphere* **317**, 137860. https://doi.org/10.1016/j.chemosphere.2023.137860.

Wanzek, T., Stults, J., Johnson, M., Field, J. & Kleber, M. 2023 Role of mineral-organic interactions in PFAS retention by AFFF-impacted soil. *Environ. Sci. Technol.* **57** (13), 5231–5242. https://doi.org/10.1021/acs.est.2c08806.

Wollin, K.-M., Batke, M., Damm, G., Freyberger, A., Gundert-Remy, U., Mangerich, A., Hengstler, J. G., Partosch, F., Schupp, T., Sonnenburg, A. & Foth, H. 2023 PFASs–restriction proposal commentary on ECHA's Annex XV restriction report, proposal for a restriction, March 2023. *Archives of Toxicology* **97** (12), 3305–3312.

Xu, Z., Ma, X., Wei, Z., Ren, G., Wu, Z., Man, Q., Zhou, B., Liu, H. & Yuan, D. 2022 A novel fate and transport model for evaluating the presence and environmental risk of per-/poly-fluoroalkyl substances (PFASs) among multi-media in Lingang hybrid constructed wetland, Tianjin, China. *Chemosphere* **291**, 132724. https://doi.org/10.1016/j.chemosphere.2021.132724.

Zeng, X., Lodge, C., Dharmage, S., Bloom, M., Yu, Y., Yang, M., Chu, C., Li, Q., Hu, L., Liu, K., Yang, B. & Dong, G. 2019 Isomers of per- and polyfluoroalkyl substances and uric acid in adults: isomers of C8 health project in China. *Environ. Int.* **133**. https://doi.org/10.1016/j.envint.2019.105160.

Zhang, S. & Lerner, D. 2012 Review of physical and chemical properties of perfluorooctanyl sulphonate (PFOS) with respect to its potential contamination on the environment. *AMR* **518–523**, 2183–2191. https://doi.org/10.4028/www.scientific.net/AMR.518-523.2183.

Zhou, Z., Liang, Y., Shi, Y., Xu, L. & Cai, Y. 2013 Occurrence and transport of perfluoroalkyl acids (PFAAs), including short-Chain PFAAs in Tangxun Lake, China. *Environ. Sci. Technol.* **47** (16), 9249–9257. https://doi.org/10.1021/es402120y.

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