Proceedings of the Indian National Science Academy (2026) 92:869–874
https://doi.org/10.1007/s43538-025-00485-0

REVIEW ARTICLE

PFAS contamination: regulatory landscape and future perspectives for India

Jajati Mandal[1] · **Santanu Majumder**[2] · **Debapriya Mondal**[1]

Received: 11 April 2025 / Accepted: 12 June 2025 / Published online: 2 July 2025
© Indian National Science Academy 2025

Abstract
This article highlights the escalating concern of PFAS (Per- and Polyfluorinated Alkyl Substances) contamination, which poses significant global concern and potentially serve implications for India. It offers a comprehensive overview of the types of PFAS, including sources, pathways, and regulatory challenges they present. Additionally, the article examines the regulatory limits proposed and followed by United States Environmental Protection Agency (USEPA), European Union (EU) and guidelines followed in United Kingdom, Australia and New Zealand. Furthermore, it provides an update on the present status of PFAS research and contamination in India and outlines the necessary steps to mitigate this contaminant in the long-term following the non-sum zero approach derived from game theory.

Keywords PFAS · Contamination · Regulation · Risk assessment · Sustainability · Game theory

Introduction

Per- and polyfluorinated alkyl substances (PFAS) are a group of synthetic organofluorine chemical compounds that have multiple fluorine atoms attached to the alkyl chain. These substances have been widely used since the 1940s due to their high stability and water/lipid resistance (www.itrcweb.org). As a result of their wide use in industrial and commercial activities, there are now over 4700 PFAS compounds known to persist in the environment (Brennan et al. 2021). This highlights the urgent need for comprehensive toxicological research on lesser-known PFAS compounds to understand their ecological and public health impacts, particularly in the Indian context where exposure pathways may be uniquely diverse. The Organisation for Economic Co-operation and Development (OECD) definition for PFAS is: "*Any fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), i.e. with a few noted exceptions, any chemical with at least a perfluorinated methyl group (–CF_3) or a perfluorinated methylene group (–CF_2–) is a PFAS*".

PFAS include a variety of functional groups comprising of anionic, cationic, zwitterionic, and neutral chemical groups (e.g., carboxylic acid, sulfonic acid, ether sulfonate, sulfonamide, sulfonamido acetic acid, phosphate diester, acrylate, amido ammonium salt, amido betaine, and others). Additionally, depending on the manufacturing technique, there may be many isomers for a given PFAS (Costello et al. 2020). Perfluoroalkyl sulfonic acids (PFSAs) and perfluoroalkyl carboxylic acids (PFCAs), of which perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) respectively, are the most explored so far. These are the two groups within the PFAS family that have attracted the most attention due to their highly bio accumulative nature[1]. Consequently, PFOS and PFOA have been voluntarily phased out, and are on Annex B (restricted) and Annex A (eliminated) of the Stockholm Convention persistent organic pollutant lists respectively. In addition, perfluorohexane sulfonic acid (PFHxS) is now being reviewed. Due to the strength of carbon fluoride bond, PFAS resist degradation and have high stability, mobility, and persistence in nature and is present in soil, groundwater, surface water and the polar ice caps. Evidence suggests that PFAS can bioaccumulate in wildlife

✉ Jajati Mandal
J.Mandal2@salford.ac.uk

[1] School of Science, Engineering and Environment, University of Salford, Salford M5 4WT, UK

[2] Department of Life and Environmental Sciences, Bournemouth University (Talbot Campus), Fern Barrow, Poole BH12 5BB, UK

and humans and some are known to pose a potential risk of toxicity.

Further, due to their high thermal and chemical stability as well as minimal biodegradability, these are referred as 'forever chemicals'(Brennan et al. 2021). PFAS are predominantly sourced from industrial activities, including the manufacture of fluoropolymer coatings and consumer products that are resistant to heat, oil, stains, grease, and water. Additionally, they can be released from fire-fighting foams used in training and emergency response scenarios. Recently a targeted analysis of 24 PFAS on 10 insecticide formulations used in a United States Department of Agriculture (USDA) research field detected PFOS in 6 formulations, with concentrations between 3.92 and 19.2 mg kg^{-1}. Further investigations found additional PFAS in soil and plants, with PFOS being the most detected (Lasee et al. 2022). The sources and routes of PFAS exposure pathways can be observed from Fig. 1.

Exposure to humans and regulatory limits

Humans are mostly exposed to PFAS through the consumption of contaminated water and food. These chemicals stay in the body and bind to proteins rather than fats; they are primarily found in the blood, liver, and kidneys (need one or two solid references here). According to studies, PFOA and PFOS can affect the immune systems, liver and kidney function, and reproductive & developmental processes. In animal tests, both chemicals have shown to induce cancers in addition to a range of other negative impacts such as on a baby's birth weight, growth, learning, behaviour, pregnancy complications, endocrine disruption, elevated cholesterol and thyroid function. For PFOA and PFOS, certain adverse health effects may manifest at concentrations close to zero. As per latest advisory from United States Environmental Protection Agency (USEPA) the two concepts Maximum Contaminant Level Goal (MCLG) and Maximum Contaminant level (MCL) has been put forward for PFOA, PFOS, PFNA, PFHxS, and HFPO-DA (known as GenX Chemicals). Further, PFHxS, perfluorononanoic acid (PFNA), perfluorobutanesulfonic (PFBS), and HFPO-DA (commonly referred to as GenX Chemicals) as a PFAS mixture based on hazard index (HI) Per- and Polyfluoroalkyl Subs tances (PFAS) | US EPA. The MCLG is defined as: " *The level of a contaminant in drinking water below which there is no known or expected risk to health. MCLGs allow for a margin of safety and are non-enforceable public health goals*". Further the MCL is defined as: "*The highest level of a contaminant that is allowed in drinking water. MCLs are set as close to MCLGs as feasible using the best available treatment technology and taking cost into consideration.*

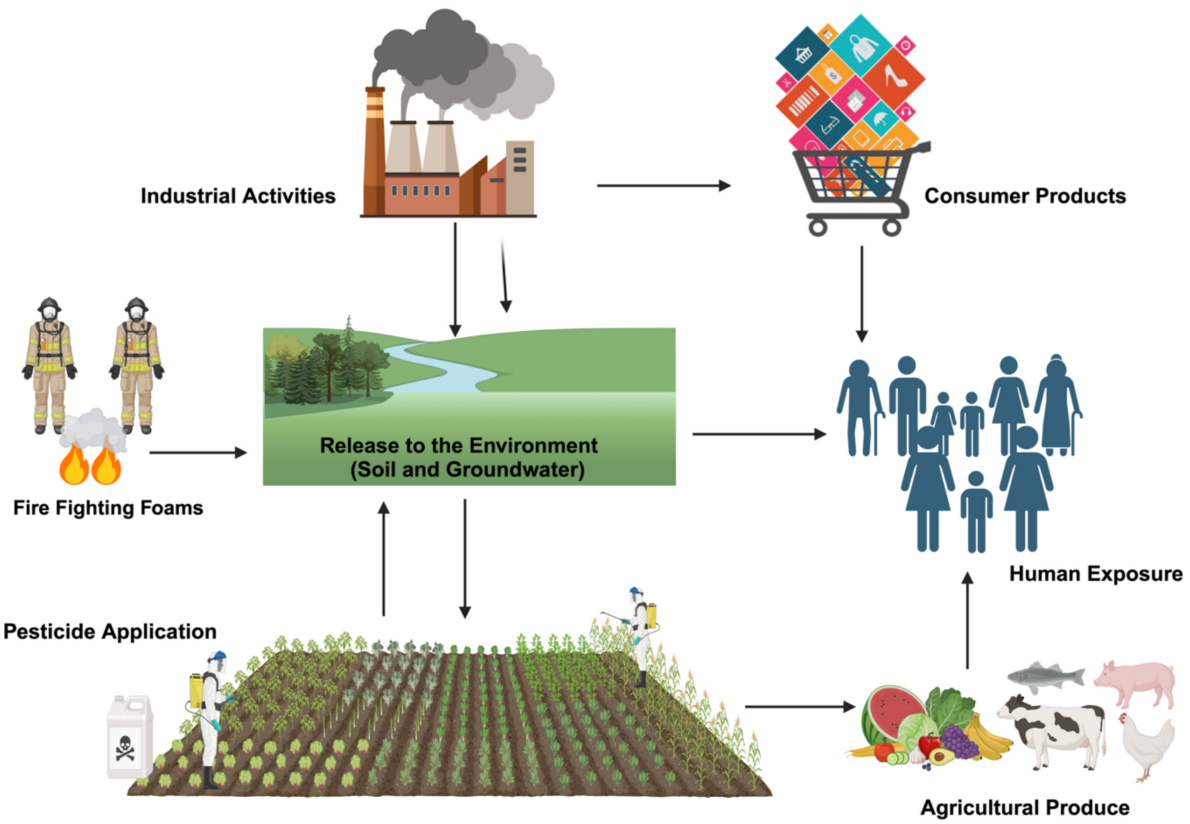


Fig. 1 PFAS exposure pathways (Created in BioRender. Mandal, J. (2025) https://BioRender.com/hbcxqlr)

Table 1 Regulatory limits of PFAS in drinking water

United states environmental protection agency (USEPA)			
PFAS		MCLG (ng L^{-1})	MCL (ng L^{-1})
PFOA		0	4.0
PFOS		0	4.0
PFNA		10	10
PFHxS		10	10
HFPO-DA (GenX chemicals)		10	10
Mixture of two or more: PFNA, PFHxS, HFPO-DA, and PFBS		HI of 1	HI of 1
Drinking water inspectorate (DWI), United Kingdom			
Tier	Concentration of any single PFAS	Summary of actions	
1-Low Risk	Less than 10	Continue monitoring and risk assessment	
2-Medium Risk	Less than 100	Continue monitoring, update risk assessments, review control measures, consult with health authorities	
3-High risk	Greater than equal to 100	Notification to health authorities, resampling of water sources, review control measures and prepare emergency contingency measures to prevent the supply of water to consumers, frequency of future monitoring for at least 12 months	
Drinking water directive (European Union)			
PFAS	Concentration	Definition	
Sum of 20 PFAS	Concentration must not exceed 100	This is a subset of 'PFAS Total' substances that contain a perfluoroalkyl moiety with three or more carbons (i.e. $–C_nF_{2n}–$, $n \geq 3$) or a perfluoroalkylether moiety with two or more carbons (i. e. $–C_nF_{2n}OC_mF_{2m}–$, n and $m \geq 1$)	
PFAS Total		PFAS Total' means the totality of per- and polyfluoroalkyl substances	
Heads of EPA Australia and New Zealand (HEPA)			
PFAS	Concentration		Definition
Sum of PFOS and PFHxS[a]	70		Where the criteria refer to the sum of PFOS and PFHxS, this means concentrations of PFOS only, PFHxS only, and the sum of the two
PFOA	560		–

MCLs are enforceable standards". Whereas HI is a long-established approach that USEPA regularly uses to quantify health risks from a chemical mixture. The HI is summation of fractions, and each fraction compares the levels of each PFAS measured in water. In United Kingdom (47 different PFAS are measured and regulated individually) the statutory standards followed by the Drinking Water Inspectorate (DWI) are Tier 1 (Low Risk): less than to 10 ng L^{-1}, Tier-2 (Medium Risk): less than 100 ng L^{-1} and Tier-3 (High Risk): greater than or equal to 100 ng L^{-1} measuring a single PFAS (DWI 2022). In 2021 the European Union (EU) drinking water directive outlined the regulatory limits for PFAS. The European Union's drinking water directives (Parliament 2020) states that 20 widespread PFAS must collectively not exceed 100 ng L^{-1}. As per the recent (2025) (HEPA 2025) PFAS National Environmental Management Plan Version 3.0 drafted by the Heads of EPA Australia and New Zealand (HEPA) for drinking water the guideline value for PFOA is 70 ng L^{-1} and it is 560 ng L^{-1} for sum of PFOS and PFHxS. The regulatory limits of PFAS in drinking water as recommended by USEPA and by DWI, UK, EU, Australia and New Zealand can be visualized in Table 1.

PFAS contamination in India and way forward (non-sum-zero approach)

At present no PFAS compounds are regulated in India. India become a party to the Stockholm Convention in 2006 and the treaty added PFOS to its global restriction list in 2009. However, India has not accepted the amendment listing this substance and it is unregulated, along with other PFAS (Brennan et al. 2021). India, a nation in the throes of development with a focus on agriculture and industrialization is home to 20% of the world population. This rapid progression has not been without its drawbacks, with notable effects on environmental quality and public health as noted by Sharma et al. (Sharma et al. 2014). Wastewater, industrial effluent, municipal, domestic wastes, and untreated sewage water that drain directly into the rivers are the major source of PFAS. The annual flux of PFOS, PFOA and PFNA in the Ganges river were 142, 24.1 and 23.0 kg respectively (Yeung et al. 2009). For Yamuna river the annual flux of PFOS, PFOA and PFNA were 168, 8.81 and 6.26 kg respectively (Yeung et al. 2009). Research has shed its light on the presence of PFAS in different matrices across various parts of India. These studies have detected PFAS in air, water, wildlife and even in human tissues. Yeung et al. 2009 reported the presence of PFOS in untreated sewage water (0.04–3.91 ng L^{-1}) and liver of Ganges river dolphin (mean = 27.9 ng g^{-1}). Presence of PFOA, PFNA and perfluorodecanoic acid (PFDA) have been reported in atmospheric particulate matter from Chennai by Ge et al., (Ge et al. 2017). In another study in 2024, Koulini and Nambi (Koulini and Nambi 2024) reported PFAS concentrations ranged from 0.10 ng to 136.27 ng L^{-1} in surface and groundwater samples collected from the Adyar River, Buckingham Canal, Chembarambakkam Lake, and a water treatment plant in Chennai. Perfluorobutanesulfonic (L-PFBS) up to 136.27 ng L^{-1} and PFOA

(up to 77.61 ng L^{-1}) were detected in all samples. They also reported increase of PFAS concentrations in the treated water from the treatment plant by 5% to 103% compared to raw water, highlighting potential concerns about water treatment processes and PFAS persistence. A study in 2016 by Sharma et al., (Sharma et al. 2016) reported the presence of 15 PFAS compounds in the Ganges river water at one or more places, with concentrations ranging from 1.3 to 15.9 ng L^{-1}. Short chain compounds were more commonly discovered, and the authors speculate that this is probably because of ongoing industry replacement. According to the study, the mean cumulative PFOS and PFOA release to the entire Ganges catchment region are 210 g day^{-1} and 240 g day^{-1}, respectively resulting an exposure to 400 million people who lives in the region. Near the river's source in Rishikesh, PFOS could not be found, but levels gradually rose downstream and peaked at the Yamuna river's confluence at Allahabad. The study also reported PFAS in irrigation groundwater and drinking water in most of the Ganges basin. Recently, presence (range) of perfluorobutanoic acid PFBA (58–2174 ng L^{-1}), PFOA (22–1530 ng L^{-1}) and PFNA (20–705 ng L^{-1}) have also been reported across 16 sampling sites of Periyar river, one of the major river systems in southern India by Binu et al., (Binu et al. 2022). Up recently (2024) in a study by Sharma et al., (Sharma et al. 2024) reported the presence total PFAS concentrations ranged from 2.46 to 469.45 ng L^{-1} in the metro area and from 123 to 321.82 ng L^{-1} in the rural region of Kamrup, Assam. Notably traces of PFAS has been found in breast milk (Tao et al. 2008) and human hair (across 14 cities of India) (Ruan et al. 2019) indicating the pervasive nature of these compounds. In addition, recent evidence from the eastern coastal regions of India confirms PFAS contamination in marine environments of Tamil Nadu and West Bengal (Hariharan et al. 2023), which raises concerns over potential bioaccumulation in seafood and risks to marine-dependent livelihoods and exports. Studies also point to road dust as a significant and understudied reservoir of PFAS contamination in urban environments of twelve states and one union territory (Yamazaki et al. 2023), which could have important implications for public exposure and regulatory monitoring frameworks.

Addressing pollution that hinders the achievement of many United Nations Sustainable Development Goals (SDG) related to zero hunger (SDG 2) and good health and wellbeing (SDG 3) should be the vision for a developing country like India. Further SDG 3.9 focuses on substantially reducing the number of deaths and illness from pollution and contamination by 2030. Pollution is a pervasive issue that transcends national boundaries. In environmental issues, particularly those involving contamination, the actions and outcomes are rarely zero-sum because the environmental, economic, and social impacts of contamination are complex and interconnected. Stopping or reducing the pollutant (PFAS) at the source is the most effective way to prevent humans and the environment from being exposed to these harmful chemicals. So, identification of the source of PFAS, understanding the routes of PFAS exposure and preventing the receptors (crops, humans, wildlife) from getting exposed should be the approach. In the Indian context, this necessitates the urgent establishment of a national PFAS inventory to systematically track the production, use, and release of PFAS across industrial sectors. Special emphasis should be placed on monitoring high-risk zones such as industrial belts, downstream catchments of major rivers like the Ganges and Yamuna, and urban clusters where untreated effluent discharge is prevalent https://cpcb.nic.in/openpdffile.php?id=UmVwb3J0RmlsZXMvMTQwM18xNjU1MzU0NzkxX21lZGlhcGhvdG8xNjQ3MS5wZGY. Regional environmental surveillance programs and health risk assessments are also crucial for guiding localised action plans. Additionally, strengthening institutional coordination between the Central Pollution Control Board (CPCB), Bureau of Indian Standards (BIS), and respective State Pollution Control Boards (SPCBs) is essential to ensure harmonised implementation of standards and enforcement protocols. These interventions embody the essence of the non-zero-sum (Simon 1987) framework, wherein cooperative governance, inclusive stakeholder engagement, and science-policy integration collectively result in synergistic environmental, economic, and public health gains.

Unlike a zero-sum game, where the gains of one player are exactly offset by the losses of others, keeping the total sum of all payoffs unchanged, a non-zero-sum game allows for outcomes where the collective gains and losses do not necessarily equal zero (Fig. 2). This highlights how, in environmental matters, actions and outcomes can benefit or harm multiple stakeholders in varying degrees. This will include i) Collaborative Remediation Efforts: When multiple parties, such as corporations, governments, and communities, collaborate to address contamination, they can create solutions where all benefit. For example, a company may invest in advanced technologies to reduce PFAS contamination or clean up contaminated sites, which not only complies with regulations but also benefits community health and improves the company's reputation. ii) Resource Allocation: In managing limited resources for environmental cleanup, different stakeholders (e.g., governmental bodies, local communities, and businesses) must negotiate how best to allocate resources to maximize the effectiveness of remediation efforts. These decisions are non-zero sum because they aim to optimize overall benefits, rather than distributing fixed losses or gains. iii) Policy and Regulation: Environmental policies and regulations should be designed in ways that incentivize sustainable practices and pollution

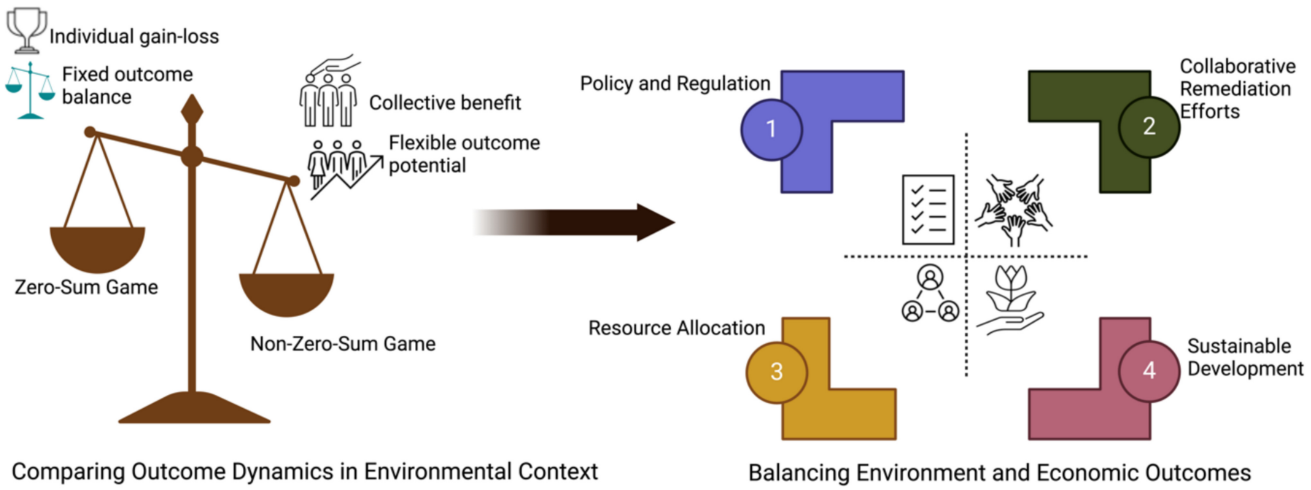


Fig. 2 Transition from Zero-Sum to Non-Zero-Sum environmental management strategies (Created in BioRender. Mandal, J. (2025) https://BioRender.com/zpr43hp)

reduction without significantly harming economic interests. iv) Sustainable Development: Efforts towards sustainable development following a non-zero-sum scenario where in environmental protection, economic growth, and social well-being are considered together, aiming for outcomes that benefit all aspects without significantly sacrificing any single dimension.

Conclusion

PFAS, which have a half-life of 3 to 5 years, can bioaccumulate in almost all the environmental matrices. At present the country lacks comprehensive data on PFAS levels in the environment matrices including humans. This makes it difficult to assess the full extent of the problem and to develop the effective strategies for dealing with it. Moreover, the vast population and significant of that residing in the rural areas in India imply that many individuals are exposed to PFAS in their everyday lives. Both the Indian government and scientific community need to take urgent action to address the PFAS problem. This includes conducting comprehensive research to understand the extent of PFAS contamination in the country raising public awareness about the associated risks, enforcing strict regulations on the production, use and disposal of PFAS-containing products following the USEPA's road map on clean-up of PFAS. Programs for ecological and human biomonitoring of PFAS is required to be initiated, along with interventions to increase public and political awareness and promote behavioural change to restrict the use of PFAS-containing products. Despite the Stockholm Convention listing PFAS as restricted chemicals, their use remains unregulated in India. However, recently the National Green Tribunal NGT has emphasized the urgent need to establish standards for PFAS in water to comply with the Water Act, 1974. The Central Pollution Control Board acknowledged rising PFAS concentrations in Indian water sources, linked to industrial shifts from developed to developing nations, and highlighted the lack of standardized monitoring and regulatory frameworks. India has initiated the regulation of PFOA and PFOS by adopting standardized methods for sampling and analysis. The Bureau of Indian Standards BIS has introduced three key methods for this purpose: ISO 3696:1987 for water quality in analytical laboratories, ISO 5667-1 for designing sampling programs and techniques, and ISO 8466-1:1990 for calibrating and evaluating analytical methods (https://www.greentribunal.gov.in). These steps mark a critical move toward establishing a framework for monitoring and controlling PFAS contamination in water. Efforts are underway, including a nationwide survey, to assess PFAS usage and inform regulatory actions. Moreover, environmental regulations cannot afford to be lenient, as weak enforcement undermines their effectiveness. There is an urgent need to rigorously implement and reinforce regulatory policies and actions. The time to act is now, as the health and well-being of both current and future generations hinge on decisive and stringent measures.

Author contributions JM conceptualized the manuscript; drafting and compiling the sources for the manuscript; SM contributed to literature survey; interpretation and editing of the manuscript; DM: critically revised the manuscript and contributed to literature survey. All the authors read and approved the manuscript.

Data availability Not Applicable

Declarations

Conflict of interest The authors have no competing interests to declare.

References

Binu, K.R., Yamashita, N., Prabhasankar, V.P., Praveenkumarreddy, Y., Shenoy, J.K., & Balakrishna, K., A First report of perfluoroalkyl substances (PFAS) in a Large West-Flowing River in Southern India. In *Impact of COVID-19 on Emerging Contaminants: One Health Framework for Risk Assessment and Remediation*, Springer Nature, Singapore, 2022, pp. 3–16

Brennan, N.M., Evans, A.T., Fritz, M.K., Peak, S.A., von Holst, H.E.: Trends in the regulation of per-and polyfluoroalkyl substances (PFAS): a scoping review. Int. J. Environ. Res. Public Health **18**(20), 10900 (2021)

Costello, M., & Lee, L.S., Sources, fate, and plant uptake in agricultural systems of per-and polyfluoroalkyl substances. *Curr. Pollut. Rep*., 2020, 1–21.

DWI (2022) Risk assessments under regulation 27 and associated reports under regulation 28 of the Water Supply (Water Quality) Regulations 2016 (2018 in Wales) for Poly and Perfluorinated Alkyl Substances. https://dwi-production-files.s3.eu-west-2.amazonaws.com/wp-content/uploads/2024/08/22155613/DWI_PFAS-Guidance_Aug-2024_FINAL-2.pdf

Ge, H., Yamazaki, E., Yamashita, N., Taniyasu, S., Ogata, A., Furuuchi, M.: Particle size specific distribution of perfluoro alkyl substances in atmospheric particulate matter in Asian cities. Environ Sci Process Impacts **19**(4), 549–560 (2017)

Hariharan, G., Sunantha, G., Robin, R.S., Darwin, R., Purvaja, R., Ramesh, R.: Early detection of emerging persistent perfluorinated alkyl substances (PFAS) along the east coast of India. Sci. Total. Environ. **902**, 166155 (2023)

HEPA 2025, PFAS National Environmental Management Plan Version 3.0, Heads of EPA Australia and New Zealand 2025. https://www.dcceew.gov.au/environment/protection/publications/pfas-nemp-3

https://cpcb.nic.in/openpdffile.php?id=UmVwb3J0RmlsZXMvMTQwM18xNjU1MzU0NzkxX21lZGlhcGhvdG8xNjQ3MS5wZGY=

https://www.greentribunal.gov.in

Koulini, G., Nambi, I.M.: Occurrence of forever chemicals in Chennai waters. India. Environ Sci Eur **36**, 60 (2024). https://doi.org/10.1186/s12302-024-00881-1

Lasee, S., McDermett, K., Kumar, N., Guelfo, J., Payton, P., Yang, Z., Anderson, T.A.: Targeted analysis and total oxidizable precursor assay of several insecticides for PFAS. J. Hazard. Mater. Letters **3**, 100067 (2022)

European Parliament (2020) DIRECTIVE (EU) 2020/2184 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 December 2020 on the quality of water intended for human consumption (recast). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32020L2184

Per- and Polyfluoroalkyl Substances (PFAS) | US EPA

Ruan, Y., Lalwani, D., Kwok, K.Y., Yamazaki, E., Taniyasu, S., Kumar, N.J., Yamashita, N.: Assessing exposure to legacy and emerging per-and polyfluoroalkyl substances via hair–The first nationwide survey in India. Chemosphere **229**, 366–373 (2019)

Sharma, B.M., Bharat, G.K., Tayal, S., Nizzetto, L., Čupr, P., Larssen, T.: Environment and human exposure to persistent organic pollutants (POPs) in India: a systematic review of recent and historical data. Environ. Int. **66**, 48–64 (2014)

Sharma, B.M., Bharat, G.K., Tayal, S., Larssen, T., Bečanová, J., Karásková, P., Nizzetto, L.: Perfluoroalkyl substances (PFAS) in river and ground/drinking water of the Ganges River basin: emissions and implications for human exposure. Environ. Pollut. Pollut. **208**, 704–713 (2016)

Sharma, A., Jorvekar, S.B., Bhowmik, S., Mohapatra, P., Borkar, R.M.: Comprehensive assessment of per and polyfluoroalkyl substances (PFAS) contamination in groundwater of Kamrup, Assam, India: occurrence, health risks, and metabolomic insights. Environ Sci Process Impacts **26**(9), 1601–1617 (2024)

Simon, F.B.: The social context of zero-sum-games and non-zero-sum-games. Int. J. Family Psychiatry **8**(3), 271–287 (1987)

Tao, L., Ma, J., Kunisue, T., Libelo, E.L., Tanabe, S., Kannan, K.: Perfluorinated compounds in human breast milk from several Asian countries, and in infant formula and dairy milk from the United States. Environ. Sci. Technol. **42**(22), 8597–8602 (2008)

Yamazaki, E., Lalwani, D., Ruan, Y., Taniyasu, S., Hanari, N., Kumar, N.J., Yamashita, N.: Nationwide distribution of per-and polyfluoroalkyl substances (PFAS) in road dust from India. Sci. Total. Environ. **892**, 164538 (2023)

Yeung, L.W., Yamashita, N., Taniyasu, S., Lam, P.K., Sinha, R.K., Borole, D.V., Kannan, K.: A survey of perfluorinated compounds in surface water and biota including dolphins from the Ganges River and in other waterbodies in India. Chemosphere **76**(1), 55–62 (2009)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.