PFAS Contamination in Key Indian States: A Critical Review of Environmental Impacts, Regulatory Challenges and Predictive Exposure

Gautam, Rajneesh Kumar, Mottaghipisheh, Javad, Verma, Saumya, Singh, Rajeev Pratap, Muthukumaran, Shobha, Navaratna, Dimuth and Ahrens, Lutz (2025) PFAS Contamination in Key Indian States: A Critical Review of Environmental Impacts, Regulatory Challenges and Predictive Exposure. Journal of Hazardous Materials Advances. p. 100748. ISSN 2772-4166

Journal of Hazardous Materials Advances 18 (2025) 100748

Contents lists available at ScienceDirect

Journal of Hazardous Materials Advances

journal homepage: www.elsevier.com/locate/hazadv

PFAS contamination in key indian states: A critical review of environmental impacts, regulatory challenges and predictive exposure

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ARTICLE INFO

Keywords:
PFAS contamination
Bioaccumulation
Predictive modeling
Fate and transport
Regulatory standards

ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) have emerged as major global environmental contaminants due to their persistence, bioaccumulation and toxicity potential. PFAS pollution is growing in India, particularly in industrial regions with limited environmental monitoring. This critical review focuses on PFAS sources, environmental fate, and transport across key Indian states, emphasizing environmental and human health risks, including drinking water exposure. A predictive model was developed to assess PFAS contamination over 30 years (2024 – 2054), revealing a strong positive correlation ($r = 0.95$, $p < 0.001$) between initial contamination levels and projected PFAS concentrations in surface water matrices, with some states anticipated to exceed safe limits. Human exposure estimation through fish consumption highlighted elevated PFAS exposure in states with high fish consumption rates, such as West Bengal and Tamil Nadu. Cumulative daily intake (CDI) analysis demonstrated substantial long-term exposure risks, incorporating water and dietary source contributions. The findings reveal critical challenges such as regulatory gaps, inadequate monitoring, and technological barriers that hinder India's ability to address PFAS contamination effectively. Comparing guideline limits globally, including those of the United States and European Union, India's regulatory framework remains in its early stages, underscoring the need for systematic monitoring and robust remediation strategies. A systematic gap analysis underscores the need for enhanced research on PFAS source tracing near industrial and urban centres. The findings emphasize the urgency of implementing stronger regulations, expanding monitoring systems, increasing public and stakeholder awareness, and informed policymaking to mitigate the growing threat of PFAS contamination in India.

List of Abbreviations

Abbreviation	Expanded Form	Units (if applicable)
AFFF	Aqueous film-forming foam	–
CDI	Cumulative daily intake	ng/kg-day, µg/kg-day
CPCB	Central Pollution Control Board	–
EPA	Environmental Protection Agency	–
ERK	Extracellular signal-regulated kinase	–
FTSA	Fluorotelomer sulfonic acid	ng/L, µg/L
GenX	Hexafluoropropylene oxide dimer acid	ng/L, µg/L
K_d	Soil water partition coefficient	L/kg
LC-MS	Liquid chromatography-mass spectrometry	–
MCL	Maximum contaminant level	ng/L
OBS	Octanesulfonic acid-based substances	ng/L, µg/L
PFAS	Per- and polyfluoroalkyl substances	–
PFBS	Perfluorobutanesulfonic acid	ng/L, µg/L
PFHxS	Perfluorohexane sulfonic acid	ng/L, µg/L
PFNA	Perfluorononanoic acid	ng/L, µg/L
PFOA	Perfluorooctanoic acid	ng/L, µg/L

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https://doi.org/10.1016/j.hazadv.2025.100748
Received 2 January 2025; Received in revised form 26 April 2025; Accepted 9 May 2025

(*continued*)

PFOS	Perfluorooctanesulfonic acid	ng/L, µg/L
PFUnDA	perfluoroundecanoic acid	ng/L, µg/L
6:2 FTS	6:2 Fluorotelomer sulfonate	ng/L, µg/L
SDGs	Sustainable Development Goals	–
WWTP	Wastewater treatment plant	–

1. Introduction

Per- and polyfluoroalkyl substances (PFAS) are a group of synthetic organic compounds that have been in use since the 1940s (Gaines, 2023). These compounds are characterized by their unique chemical structure, comprising either linear or cyclic fluorinated carbon chains $-C_nF_{2n}-$ ($n \geq 3$) or $-C_nF_{2n}OC_mF_{2m}-$ (n and $m \geq 1$) (Development, 2018). This fluorinated structure forms exceptionally strong carbon-fluorine bonds, making PFAS highly resistant to chemical, thermal, and environmental degradation. Their surfactant characteristics, hydrophobic tails and hydrophilic heads impart the properties that have driven their extensive use in applications such as non-stick cookware (Teflon), firefighting foams, stain-resistant fabrics, water-repellent textiles, food packaging, and electronics (Death et al., 2021). However, while PFAS has contributed to various technological advancements due to their chemical stability and surfactant properties, their extreme environmental persistence and resistance to degradation pose serious challenges to long-term ecological and human health (Bansal et al., 2022). The widespread use of PFAS has led to their accumulation in the environment, where they persist in water, soil, air, and even living organisms, including humans (Tang, 2023; Yamazaki et al., 2023). Over 10,000 different PFAS have been identified, with the most studied being perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) (Pontius, 2019). Short-chain perfluorocarboxylic acids (PFCAs) are defined as those containing carbon chains with fewer than eight carbon atoms (Che et al., 2021), while short-chain perfluorosulfonic acids (PFSAs) are defined as those with fewer than six carbon atoms in their perfluorinated chain (Peshoria et al., 2020). Short-chain PFAS exhibit higher mobility in aquatic environments due to their lower sorption affinity; however, they remain environmentally persistent and resistant to degradation, similar to long-chain PFAS (Nian et al., 2020). In contrast, long-chain PFCAs have eight or more carbon atoms, such as PFOA (Gagliano et al., 2020), and long-chain PFSAs have six or more carbon atoms, such as PFOS (Ateia et al., 2019). These long-chain PFASs have a strong hydrophobic nature and higher sorption potential to the solid phase (Palazzolo et al., 2022). Their persistence in biological systems and resistance to environmental degradation make them more toxicologically significant compared to short-chain PFAS (Ateia et al., 2019).

PFAS are also known to bioaccumulate in the food chain (Jala et al., 2023), meaning their concentrations can increase in organisms over time, leading to higher exposure levels (Glaser et al., 2021). This bioaccumulation and biomagnification through the food chain can lead to elevated PFAS exposure in humans, particularly those consuming contaminated fish or animal products (J.L. Domingo and Nadal, 2019). Given their environmental persistence, bioaccumulative nature, and growing links to chronic health issues, PFASs have emerged as a major concern for global environmental and public health systems (Fenton et al., 2021).

Due to their strong carbon-fluorine bonds, PFAS are resistant to degradation and are not entirely removed by conventional wastewater treatment plant (WWTP) processes (Kucharzyk et al., 2017). Because of their persistence and mobility, PFAS can escape into the environment and undergo long-range atmospheric and aquatic transport. This leads to their detection even in remote ecosystems such as the Arctic (Brusseau et al., 2020). PFAS enter the environment through various pathways, including industrial emissions, WWTP discharges, landfill leachates, and firefighting foams (Möller et al., 2010). PFAS can also be released into the environment through diffuse pathways such as the usage of consumer products, atmospheric deposition, and run-off (John et al., 2022). Their high mobility in water and resistance to natural degradation means that once released, they can travel long distances in the aqueous phase and contaminate, for example, drinking water sources (Ahrens, 2011; McCleaf et al., 2017; Sörengård et al., 2022).

Given their pervasive presence, PFAS contamination has emerged as a global environmental concern, affecting surface and drinking water supplies on a global scale such as the United States (U.S.) (Wickham and Shriver, 2021; Ng et al., 2021), the European Union (EU) (Reinikainen et al., 2024; Brunn et al., 2023), China (Jia et al., 2023), and Australia (Banwell et al., 2021). While global regulatory agencies have begun enforcing stringent thresholds, significant gaps remain in developing nations, particularly South Asia (Singh et al., 2023). India's rapid industrialisation, urbanisation, and limited PFAS oversight (Sörengård et al., 2022) have positioned the country as a critical yet underreported frontier in the global PFAS contamination narrative. Understanding PFAS dynamics in India is thus essential for national environmental protection and informing broader global models of PFAS fate, exposure, and risk under diverse socioeconomic and regulatory conditions. Research indicates that regions with heavy industrial activity, such as textile manufacturing, chemical production, and firefighting training sites, are significant sources of PFAS pollution in the environment (Sharma et al., 2024).

PFAS contamination has been increasingly documented across India, particularly in environmental matrices such as groundwater, surface water, road dust, and food products (Yamazaki et al., 2023; Hariharan et al., 2023). Notably, studies have reported PFAS detections in Tamil Nadu and Assam groundwater sources used for drinking water (Hariharan et al., 2023; G. Jha et al., 2021), while surface and drinking water samples from Chennai revealed elevated concentrations, likely linked to industrial activity (G. Koulini and Nambi, 2024). The detection of PFAS in consumer items like tea bags, where compounds such as PFOS, perfluorohexanesulfonic acid (PFHxS) and perfluoroundecanoic acid (PFUnDA) were found in 90 % of tested samples (Jala et al., 2023) highlights the diversity of exposure pathways. Despite mounting evidence, India's regulatory framework remains underdeveloped compared to the U.S. and the EU (Gobelius et al., 2018) (Table 1). While initial monitoring has begun, comprehensive standards for PFAS in water, soil, or food are still lacking (Singh et al., 2023), even as global counterparts continue to implement stringent exposure limits (Abunada et al., 2020).

The U.S. Environmental Protection Agency (EPA) has set stringent enforceable limits on critical PFAS compounds in the U.S. with the maximum contaminant levels (MCL) for PFOA and PFOS as 4 ng/L, with limits for other PFAS, such as PFHxS, PFNA (perfluorononanoic acid), and GenX, set at 10 ng/L (Fenton et al., 2021; Wang et al., 2017). PFBS is included in the cumulative hazard index approach with PFHxS, PFNA, and GenX (HFPO-DA), which collectively must remain below a hazard index threshold of 1 (unitless) (EPA, 2023). Additionally, the US EPA employs a hazard index approach for mixtures of PFHxS, PFNA, GenX, and PFBS, with a threshold of 1 (unitless) (Brunn et al., 2023). This approach reflects growing concerns over the cumulative effects of multiple PFAS. In contrast, India has not established enforceable national limits on PFAS concentrations in drinking water or other environmental media (India-Aldana et al., 2023). While some monitoring efforts have been implemented, the lack of comprehensive data on PFAS contamination in the Indian environment hinders effective regulation. More research is needed to assess the extent of PFAS contamination and develop appropriate policies to safeguard public health. The absence of stringent regulatory frameworks underscores the need for proactive measures in India, as PFAS contamination will likely increase without intervention (Griffin et al., 2022).

While several valuable reviews have discussed PFAS contamination globally and within India (Das and Janardhanan, 2022), these studies have primarily emphasized policy acceleration and general

Table 1
PFAS drinking water standards in selected countries and regions (Gaines, 2023; Development, 2018; Death et al., 2021; Bansal et al., 2022; Tang, 2023).

Country/ Region	PFOA (ng/L)	PFOS (ng/L)	PFHxS (ng/L)	PFNA (ng/L)	GenX (ng/ L)	PFBS (ng/L)	Other (ng/L)	Regulatory Body
USA (EPA)	4	4	HI < 1	HI < 1	HI < 1	HI < 1	HI < 1	Environmental Protection Agency (EPA)
European Union	100 ($\sum_{20}$PFAS)[b]	100 ($\sum_{20}$PFAS)[b]	100 ($\sum_{20}$PFAS)[b]	100 ($\sum_{20}$PFAS)[b]	NA	100 ($\sum_{20}$PFAS)[b]	500 (Total PFAS)	European Commission
Canada	200	200	600	NA	NA	NA	NA	Health Canada
Australia	560	70	NA	NA	NA	NA	NA	Australian Drinking Water Guidelines
Japan	50	50	NA	NA	NA	NA	NA	Ministry of Health, Labour and Welfare
India[a]	NA	NA	NA	NA	NA	NA	NA	Central Pollution Control Board (CPCB)

PFOA: perfluorooctanoic acid, PFOS: perfluorooctanesulfonic acid, PFHxS: perfluorohexane sulfonic acid, PFNA: perfluorononanoic acid, GenX: hexafluoropropylene oxide dimer acid, PFBS: perfluorobutanesulfonic acid.

HI approach: This refers to the US EPA's hazard index (HI) method for PFHxS, PFNA, GenX, and PFBS (threshold value = 1, unitless).

[a] India has no established enforceable limits for PFAS in drinking water.

[b] EU limit for 20 PFAS compounds, enforced under the Drinking Water Directive.

[b]$\sum_{20}$PFAS includes perfluorobutanoic acid (PFBA), perfluoropentanoic acid (PFPeA), perfluorohexanoic acid (PFHxA), perfluoroheptanoic acid (PFHpA), perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA), perfluorodecanoic acid (PFDA), perfluoroundecanoic acid (PFUnDA), perfluorododecanoic acid (PFDoDA), perfluorotridecanoic acid (PFTrDA), perfluorotetradecanoic acid (PFTeDA), perfluorobutanesulfonic acid (PFBS), perfluoropentanesulfonic acid (PFPeS), perfluorohexane sulfonic acid (PFHxS), perfluoroheptanesulfonic acid (PFHpS), perfluorooctanesulfonic acid (PFOS), perfluorononanesulfonic acid (PFNS), perfluorodecanesulfonic acid (PFDS), perfluoroundecanesulfonic acid (PFUnDS), perfluorododecanesulfonic acid (PFDoDS), perfluorotridecanesulfonic acid (PFTriDS).

NA = not available.

contamination patterns. Building upon these contributions, the present review further expands the knowledge by integrating predictive modeling to provide comprehensive state-level assessments, detailed evaluations of emerging remediation technologies, and an in-depth comparative analysis of India's regulatory frameworks in relation to global standards. This integrated approach addresses existing knowledge gaps and supports informed policy-making aligned with global sustainability goals, particularly SDG 6 (Clean Water and Sanitation) and SDG 12 (Sustainable Consumption and Production) (Hák et al., 2016).

The primary aim of this review is to critically assess the current state of PFAS contamination across key Indian states, focusing on understanding the environmental distribution, fate, transport mechanisms, and associated human health risks. Specifically, this review aims to: (1) systematically summarize and evaluate the occurrence and sources of PFAS contamination in various environmental matrices, including water, soil, air, and biota; (2) identify and discuss existing regulatory gaps and challenges in managing PFAS contamination in India; and (3) employ predictive modeling to forecast future PFAS exposure scenarios in critical environmental matrices, highlighting areas likely to exceed established safety thresholds within the Indian context. By achieving these objectives, the study aims to provide comprehensive insights and actionable recommendations for policymakers, researchers, and environmental managers to address the escalating issue of PFAS contamination effectively.

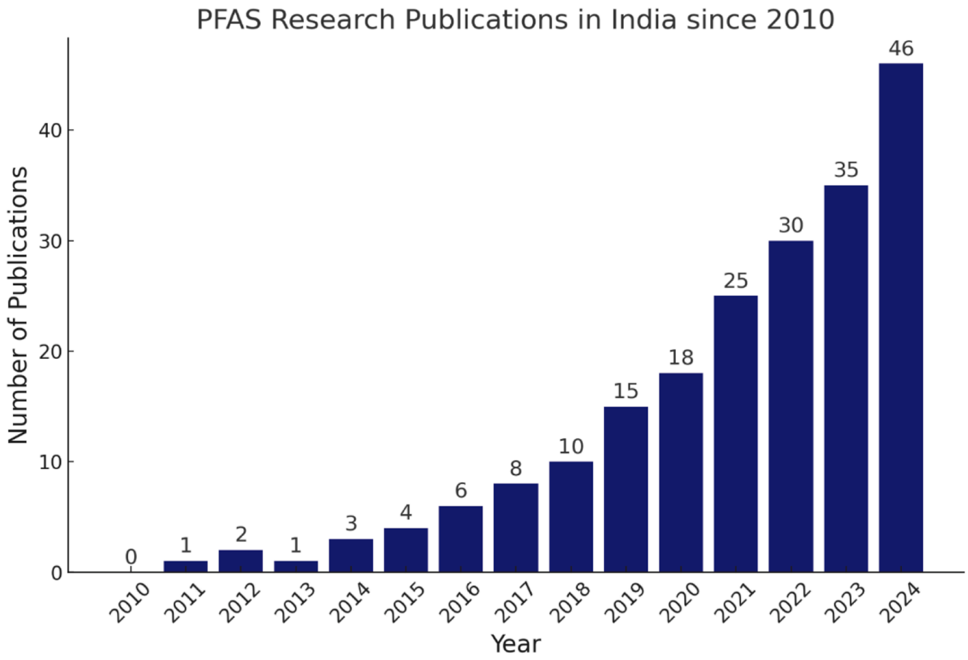

Fig. 1. PFAS research publications in India since 2010 (Data retrieved from Scopus using the keywords: ("Per- and polyfluoroalkyl substances" OR PFAS or PFOA or PFOS or PFHxS or "Perfluorinated compounds") AND (India or "Indian environment") AND (contamination or pollution or remediation).

2. Overview of PFAS research in india

Research on PFAS has expanded significantly in recent years, driven by growing awareness of their environmental persistence and potential health risks. Between 2000 and 2010, global PFAS contamination (Möller et al., 2010; Ahrens, 2011; Haukås et al., 2007; Clara, 2008) focused predominantly on the U.S. and Europe, but research in India was limited. However, PFAS research in India gained momentum after 2015, primarily due to advancements in detection techniques and a growing recognition of PFAS-related environmental and public health concerns (Fig. 1).

The initial studies in India (post-2015) focused mainly on understanding the occurrence and distribution of PFAS in industrial regions (SHUKLA). Studies identified industrial effluents as a primary PFAS source in states such as Gujarat and Maharashtra, with significant heavy industrial activities (Ruan et al., 2019; Garg et al., 2020) (Figure S1 in Supplementary Information (SI). Tamil Nadu, another state with substantial industrial output, also showed growing research interest as studies began documenting PFAS contamination in groundwater and drinking water sources (Hariharan et al., 2023). From 2015 to 2020, interest in PFAS research in India expanded rapidly, with studies conducted in regions such as Assam and West Bengal, focusing on river systems and coastal areas where PFAS contamination was detected in surface water and sediments (Sharma et al., 2024).

This period marked an increase in nationwide research efforts, with PFAS contamination becoming a concern beyond industrialised regions. Studies began to investigate the presence of PFAS in urban areas, with research on road dust contamination in cities like Uttar Pradesh revealing new sources of PFAS pollution (Yamazaki et al., 2023). However, the number of peer-reviewed publications in India (35 −45 in 2023 and 2024) is still insignificant compared to the U.S. (over 1200 in 2023) and Europe (approximately 950 in 2023) when using the keyword "PFAS contamination" in Scopus (Ismail et al., 2023). This disparity highlights the limited focus on PFAS research in India despite the growing concerns about its environmental and health impacts. Most PFAS studies have been conducted globally in regions with advanced regulatory frameworks, such as the U.S. and EU, where data availability and monitoring programs support more extensive investigations (Brennan et al., 2021). In contrast, India's PFAS research remains nascent, primarily concentrated in isolated studies of specific industrial zones or environmental matrices. This underrepresentation underscores the need for increased research funding, interdisciplinary collaborations, and robust national monitoring programs to understand PFAS dynamics in Indian ecosystems better and inform evidence-based policy interventions.

The research focus in India has evolved to encompass several key areas: municipal and industrial WWTP effluents, groundwater contamination, food packaging and consumer goods, and environmental transport. More recently, research has expanded to consumer goods, such as food packaging and household items, with studies in Maharashtra and Andhra Pradesh identifying PFAS contamination in everyday products like tea bags (Jala et al., 2023). While initial studies (2010 - 2015) concentrated on industrial discharges, the scope has expanded to include urban and rural areas, river systems, and consumer goods (2016 - 2024). The increasing attention on regions like Assam, West Bengal, and Uttar Pradesh highlights the nationwide impact of PFAS contamination, prompting a call for more comprehensive research and regulatory responses (G. Jha et al., 2021).

3. Key sources of PFAS and PFAS precursors in india

PFAS contamination in India stems from various sources, including industrial activities, urban wastewater, consumer products, and agricultural practices. In addition to known PFAS, PFAS precursors, which degrade into persistent PFAS over time, represent a significant challenge. This section discusses the primary sources of PFAS and their precursors, offering a detailed examination of their pathways into the environment. The pathway of PFAS (Agency, 2021), from industrial discharges, firefighting foams, and agricultural run-off into rivers and groundwater, is illustrated in Fig. 2, which depicts how these chemicals spread through water and soil, eventually contaminating drinking water and crops.

3.1. Industrial sources

Industries, particularly chemical manufacturing, textile production, and paper processing, significantly contribute to PFAS contamination in India (Sharma et al., 2024). Studies have reported that concentrations of PFOS and PFOA in effluents from textile, leather, and fluoropolymer-related industries can range from 100 to 10,000 ng/L (Newland et al., 2023). Additionally, precursor compounds such as 6:2 fluorotelomer sulfonate (6:2 FTSA) have been detected at concentrations up to 20,000 ng/L (Per, 2021), depending on the specific industrial processes and the efficacy of wastewater treatment systems (Barisci and Suri, 2021). These high concentrations underscore the need to monitor and regulate PFAS discharges from industrial sources. PFAS, including PFOA and PFOS, are commonly used in these industries due to their non-stick and water-resistant properties (Cousins et al., 2019). Effluents from industrial activities, particularly in Gujarat, Maharashtra, and Tamil Nadu, often contain high levels of PFAS and their precursors (G.V. Koulini et al., 2024). Textile industries, for instance, use fluorinated surfactants to impart water- and stain-resistant properties to fabrics (Rao and Baker, 1994). The wastewater generated from these factories often contains PFAS precursors, such as fluorotelomer alcohols (FTOHs) and fluorotelomer sulfonates (FTSAs) (Cantoni et al., 2024). When released into nearby water bodies, these precursors may degrade to stable PFAS like PFCAs and PFSAs, leading to long-term contamination of rivers and lakes (Drage et al., 2023). Textile hubs in Tamil Nadu, including cities like Tiruppur and Karur, have been identified as hotspots for PFAS pollution due to the heavy use of these chemicals in the textile sector (Hariharan et al., 2023). In addition to textiles, the chemical manufacturing industry in Gujarat and Maharashtra also contributes significantly to PFAS contamination (Mohapatra and Basu, 2023). Fluorochemical plants that produce products like fire retardants and non-stick coatings are known to release PFAS compounds through wastewater discharge (Arora et al., 2023). These plants release significant quantities of precursor compounds that degrade into more persistent PFAS (Costello and Lee, 2020). Studies have shown that PFAS contamination in rivers near these industrial regions can persist for decades (K.R. Binu et al., 2022; IPEN, 2019; G. Jha et al., 2021), particularly without advanced wastewater treatment technologies.

3.2. Urban water and wastewater

Urban wastewater is a significant pathway for PFAS contamination in India's densely populated cities (Kurwadkar et al., 2022). WWTPs in cities like Mumbai, Delhi, and Chennai lack the advanced treatment technologies necessary to remove PFAS from municipal wastewater (Cantoni et al., 2024; Lenka et al., 2021). As a result, PFAS and their precursors pass through the treatment process and are discharged into rivers, lakes, and coastal waters. In Chennai, for example, effluents from WWTPs contain significant levels of PFOS, PFOA, and precursor compounds such as 6:2 fluorotelomer sulfonate (6:2 FTSA) (G.V. Koulini and Nambi, 2024). These compounds may eventually degrade into more persistent PFAS, contributing to long-term contamination of nearby water bodies like the Adyar and Cooum rivers (Yamazaki et al., 2023). Also, stormwater runs off from urban areas, which picks up PFAS from roads, industrial sites, and household products, contributing to contamination (Banerjee, 2023). Urban run-off during the monsoon season can carry large amounts of PFAS and precursors into surface water systems, aggravating the issue (Coates and Harrington, 2024). This contamination is prevalent in cities like Delhi, Kolkata, and

Fig. 2. Pathways of PFAS movement in the environment (Adapted from (Gaines, 2023)).

Bengaluru, where rapid urbanisation and industrialisation have increased PFAS loads in water systems (Ganeshamurthy et al., 2008).

3.3. *Landfills and waste incineration*

Landfills and waste incineration are significant yet often overlooked sources of environmental PFAS contamination. PFAS-containing consumer products, industrial waste, and discarded firefighting foam accumulate in landfills (O'Connor et al., 2022), which can leach into surrounding soil and groundwater through landfill leachate (Chidichimo et al., 2020). Studies have shown that leachate from landfills can contain high concentrations of PFAS, which then migrate into nearby water systems, posing risks to human health and aquatic ecosystems (Abunada et al., 2020; Gunarathne et al., 2023; Qian et al., 2024). Similarly, waste incineration, although aimed at reducing landfill volume, can release PFAS into the atmosphere when PFAS-containing materials are burned (Tolaymat et al., 2023). During incineration, incomplete combustion or low-temperature processes may transform PFAS into other harmful byproducts, which can be deposited onto soil and water surfaces through atmospheric deposition (Weber, 2023). This dual pathway, leachate from landfills and emissions from waste incineration, highlights the need for stricter controls on waste management practices, including monitoring PFAS in landfill leachate and adopting high-temperature incineration techniques to minimize PFAS emissions (Jelínek et al., 2024). Implementing these measures is particularly critical in India, where underdeveloped waste segregation and treatment infrastructure increase the risk of uncontrolled PFAS emissions from landfill leachate and incineration processes.

3.4. *Consumer products*

A significant source of PFAS in urban and rural environments is the widespread use of consumer products containing these chemicals (Donley et al., 2024). Food packaging materials, including fast-food wrappers, disposable food containers, and microwave popcorn bags (Ramírez Carnero et al., 2021), are often coated with PFAS to prevent grease and liquid from seeping through (Kwiatkowski et al., 2020). These products contain significant PFAS precursors, including polyfluoroalkyl phosphoric acid diesters (diPAPs), which may degrade into PFCAs in landfills, wastewater treatment, or the environment (Zhang et al., 2022). When improperly disposed of, these materials, the precursors leach into soil and groundwater, contributing to contamination (Pradhan, 2023). In addition, the incineration of these materials releases PFAS into the air, further spreading contamination through atmospheric deposition (Zhang et al., 2023). In addition to food packaging, personal care products such as waterproof cosmetics and stain-resistant textile treatments also contribute to PFAS pollution (Perera and Meegoda, 2024). These products contain precursors that are washed off during use and end up in the wastewater system. Since most WWTPs cannot effectively remove PFAS precursors, they end up in surface and groundwater and may degrade to stable PFAS (Crone et al., 2019).

3.5. *Firefighting foams*

Firefighting foams, particularly aqueous film-forming foams (AFFF), have been widely used in India for firefighting training and emergencies (Seow, 2013). These foams contain a range of PFAS, including PFOS and

PFOA, and precursor compounds, such as 6:2 FTSA (Adamson et al., 2020). AFFF has been extensively used in airports, military installations, and chemical plants across India (G. Koulini et al., 2024). Over time, the PFAS in these foams can migrate through soil and water, contaminating surface water and groundwater (Sörengård et al., 2022; Hatton et al., 2018). In Karnataka, recent studies have identified elevated PFAS concentrations in groundwater near airports where AFFFs have been frequently used (Garg et al., 2020). Using these foams is particularly problematic at sites like Chennai International Airport and military bases in Pune and Patna, where PFAS-laden foams have contaminated surrounding water bodies (G. Koulini et al., 2024).

Similarly, in Assam, PFAS contamination has been detected in the Brahmaputra River near industrial sites (Sharma et al., 2024), raising concerns about the safety of drinking water sources in the region. PFAS precursor compounds may degrade into stable PFAS that persist in the environment for a long time (McGarr et al., 2023). This contamination poses a significant challenge to remediation efforts, as the precursors continuously generate PFAS over time, contributing to ongoing contamination even after the initial source has been removed. Despite the known dangers associated with AFFFs, regulations governing their use and disposal in India remain inadequate, further contributing to the contamination of vital water sources.

3.6. *Agricultural practices and biosolids*

Using biosolids derived from treated sewage sludge as a fertilizer in agriculture is another primary source of PFAS contamination (Marchuk et al., 2023). Biosolids can contain high concentrations of both PFAS and their precursors, which are transferred to agricultural soils when these fertilizers are applied (Ghisi et al., 2019). Over time, PFAS precursors may degrade into PFAS, contaminating soil and crops grown in these fields. In states like Punjab and Haryana, where biosolids are commonly used as fertilizers, PFAS contamination has been detected in soil samples and crops irrigated with contaminated water (Corsolini et al., 2012). This contamination affects soil quality and introduces PFAS into the human food chain, as crops take up PFAS and potentially expose humans (G. Jha et al., 2021). Agricultural run-off from fields treated with biosolids further contributes to PFAS contamination in nearby rivers and lakes (Gaonkar et al., 2021). In addition to biosolids, irrigation with PFAS-contaminated groundwater or surface water is another source of PFAS in agricultural products (Pepper et al., 2023). This is particularly problematic in regions like West Bengal and Uttar Pradesh, where contaminated groundwater irrigates large swathes of farmland, further spreading PFAS through the food supply chain (Hariharan et al., 2023).

The diverse pathways of PFAS release outlined above, from industrial discharges and landfills to firefighting foam usage and wastewater treatment plants, highlight the complexity of PFAS environmental dissemination in India. These sources contribute to varying degrees of contamination across different ecosystems. The following section (Section 4) builds upon this framework by presenting measured concentrations of PFAS across environmental matrices such as water, sediment, and biota, offering spatial insights into contamination patterns and regional hotspots.

4. Occurrent of PFAS in the environment and human exposure

The presence of PFAS in India has become an increasing environmental concern due to their persistence and widespread contamination across various environmental matrices (G. Koulini et al., 2024). These matrices include surface water, groundwater, sediments, air, road dust, biota, and humans. This section presents a detailed account of PFAS occurrence in India, supported by concentration data from various regions (Table 2).

4.1. *Surface water*

Surface water systems in India have been significantly impacted by PFAS contamination, particularly in regions with high industrial and urban activity, as shown in Table 2. In Chennai, the concentrations of PFOS and PFOA in surface water have been measured at 3 to 93 ng/L (G.

Table 2
Overview of PFAS detected in various environmental matrices across India.

Matrix	Type of PFAS	Locations	Concentration Range	Key Findings	References
Surface Water	PFSAs, PFCAs, FOSA, PFBS, PFOA, PFOS	Chennai, Goa, Coimbatore, Patna, Varanasi, Ganges, Kaveri River, Tamil Nadu, West Bengal	<1.5 – 136.27 ng/L	PFOS and PFOA contamination have been detected in rivers and coastal regions, with the highest concentrations in Chennai and Ganges River waters.	(Yamazaki et al., 2023; Pontius, 2019; Che et al., 2021; Peshoria et al., 2020)
Groundwater	PFOA, PFOS, PFBS	Chennai, West Bengal, Patna, Ganges	<MQL – 10.2 ng/L	PFAS is detected in groundwater, particularly in areas near industrial activities and urban centres like Chennai.	(Nian et al., 2020; Gagliano et al., 2020; Ateia et al., 2019)
Sediments	PFOA, PFOS	Ganges, Sundarban Wetlands, Coastal Sediments (Tamil Nadu, West Bengal)	<MQL – 14.09 ng/g dry weight	Sediments act as reservoirs for PFAS, with significant accumulation observed in the Ganges and coastal sediments in Tamil Nadu and West Bengal.	(Gagliano et al., 2020; Palazzolo et al., 2022)
Air	FTOs, FTAs, FTOHs, FOSAs	Howrah, Kolkata, Assam, Chennai, Bangalore, Mumbai	54 – 820 pg/m^3	Airborne PFAS measured particulate matter and ambient air in urban areas, highlighting the role of vehicular emissions and industrial activities.	(Jala et al., 2023; Glaser et al., 2021; J.L. Domingo and Nadal, 2019)
Road Dust	PFSAs, PFCAs, FOSAs/AAs, FTUCAs, FTSAs	Jammu & Kashmir, Uttar Pradesh, Tamil Nadu, Maharashtra, Gujarat, Kerala, West Bengal, Odisha	0.00158 – 0.861 ng/g dry weight	High PFAS concentrations in road dust from urban areas indicate pollution from vehicular emissions and road runoff in densely populated regions.	(Fenton et al., 2021)
Biota	PFCAs, PFSAs, FOSAs	Ganges River (Dolphins, Fish, Shrimp), Chennai (Pigs)	0.093–200 ng/g wet weight	Bioaccumulation of PFAS is observed in aquatic species and livestock, raising concerns about the entry of PFAS into the food chain through the consumption of contaminated animals.	(Yamazaki et al., 2023; Kucharzyk et al., 2017)
Humans	PFOS, PFHxS, PFOA, PFNA	Human Serum (Chennai, Coimbatore), Breast Milk (Chennai, Kolkata, Chidambaram)	<3 ng/mL in serum, <1.66–335 pg/mL in breast milk	Human exposure to PFAS through contaminated drinking water and food is evident from serum and breast milk studies, particularly in Chennai and Coimbatore.	(Kucharzyk et al., 2017; Brusseau et al., 2020)

PFSAs = perfluorosulfonic acids; PFCAs = perfluorocarboxylic acids; FOSA = perfluorooctane sulfonamide; FTOs = fluorotelomer olefins; FTAs = fluorotelomer acrylate; FTOHs = fluorotelomer alcohols; FTUCA = fluorotelomer unsaturated carboxylic acids; FTSAs = fluorotelomer sulfonic acids; MQL = method quantification limit.

Koulini et al., 2024). The primary sources of this contamination are wastewater discharges from industries, including textile manufacturing and chemical processing, and run-off from urban areas (Singh et al., 2022). PFAS effluents often reach rivers and other surface water bodies without adequate treatment in these industrial hubs. In other locations such as Goa, Coimbatore, Patna, and Varanasi, surface water contamination is comparatively lower in less industrialised areas (G. Koulini and Nambi, 2024). However, the detection of PFAS still reflects contributions from smaller-scale industrial activity, urban runoff, and consumer products containing PFAS concentrations ranging from <0.04 to 23 ng/L (G.V. Koulini et al., 2024). The widespread use of firefighting foams in airports and military bases is another contributing factor to the presence of PFAS in surface waters near these locations (Milley et al., 2018). PFAS concentrations in surface and groundwater samples along the Ganges and several other rivers have been reported at levels ranging below the method quantification limit (MQL) to 10 ng/L (Corsolini et al., 2012). Sources in this region include industrial discharges, WWTP effluents, and agricultural runoff. The Ganges is particularly vulnerable due to the large population and the concentration of industries along its banks. Other river systems, such as the Kaveri, Vellar, and Tamiraparani in Tamil Nadu, have shown perfluorohexanoic acid (PFHxA) and PFOS concentrations typically reported to be ≥1 ng/L (G. Sunantha and Vasudevan, 2016) and in some cases exceeding 10 ng/L (G.V. Koulini et al., 2024; G.V. Koulini and Nambi, 2024), likely originating from textile and tannery industries in the region (Tang, 2023; Singh et al., 2023).

4.2. Groundwater

Groundwater is an essential resource for drinking and irrigation in India, making its contamination by PFAS particularly concerning. Studies in Chennai have revealed high levels of PFAS in groundwater, with concentrations ranging from 0.1 to 136 ng/L (G. Koulini and Nambi, 2024). While international drinking water standards (such as those set by the U.S. EPA and EU) (Wang et al., 2017; EPA, 2023; Brauns et al., 2024; K. Binu et al., 2022) apply to individual PFAS compounds (e.g., 4 ng/L for PFOA and PFOS), the observed total PFAS levels in these waters suggest potential exceedances of safety thresholds if individual compounds are present at significant concentrations. The groundwater contamination in Chennai is primarily attributed to industrial discharges and inadequate wastewater treatment before it is allowed to infiltrate the groundwater table. Leaching from landfills and improper disposal of PFAS-containing products also contribute to the contamination (Travar et al., 2021). In West Bengal, groundwater contamination has been detected at lower concentrations, often below the method quantification limit (Das and Janardhanan, 2022). However, even low levels of PFAS contamination, often resulting from industrial leaching and atmospheric deposition, can pose long-term environmental and health risks and should not be overlooked (Solan et al., 2023). Using contaminated groundwater for drinking, agriculture, and livestock further exacerbates exposure risks in rural areas. The Ganges River basin, which supports a large population, shows contamination in both surface and groundwater sources, likely due to industrial and agricultural runoff and urban wastewater inputs (Sharma et al., 2016).

4.3. Sediment

PFAS can accumulate in sediments, where they may persist for extended periods and slowly release back into surrounding water bodies (Abunada et al., 2020). In the Ganges River and the Sundarban wetlands, PFOS and PFOA were detected in sediment samples, with concentrations ranging from below the MQL to 14 ng/g dry weight (dw) (Corsolini et al., 2012; Sharma et al., 2016). This indicates that PFAS contamination is not limited to the water column but extends to riverbeds and wetlands, which act as reservoirs for these chemicals. In Tamil Nadu and West Bengal coastal regions, sediment samples showed PFAS concentrations between 1.7 and 8.2 ng/g dw (G. Sunantha and Vasudevan, 2016). The sources of PFAS in these sediments are likely similar to surface waters, industrial discharges, urban runoff, and atmospheric deposition (Ehsan et al., 2024). Sediment contamination can have long-term ecological impacts, affecting benthic organisms and other wildlife that rely on sediment-dwelling species for food (O'Connor et al., 2022).

4.4. Atmosphere

PFAS have also been detected in the atmosphere (Faust, 2023). Studies in urban centres such as Kolkata, Howrah, Chennai, and Mumbai recorded concentrations of FTOHs, fluorotelomer acids (FTAs), and other PFAS ranging from 54 to 820 pg/m^3 (SHUKLA). These airborne PFAS are likely emitted from industrial activities, manufacturing processes that utilise PFAS, WWTP, landfills and diffuse sources (Meegoda et al., 2020; Ahrens et al., 2011). In Delhi and Gujarat, particulate matter samples revealed PFAS concentrations ranging from non-detectable to 2.4 pg/m^3 (IPEN, 2019). The presence of PFAS in the atmosphere highlights the potential for long-mospheric transport, whereby these chemicals can travel from urban and industrial areas to more remote regions. Vehicular emissions and dust resuspension from contaminated surfaces are essential contributors to airborne PFAS levels (on the Identification, I.W.G. 2023).

4.5. Road dust

Road dust is another medium through which PFAS is transported in urban environments (Yamazaki et al., 2023). PFAS concentrations in road dust samples collected from Jammu & Kashmir, Uttar Pradesh, Bihar, Maharashtra, and Tamil Nadu ranged from 1.6 pg/g to 860 pg/g dw for $\sum$PFAS (multiple PFAS, including PFOA, PFOS, PFHxA, and others) (Yamazaki et al., 2023). Concentrations in road dust are primarily linked to vehicular emissions, road run-off, and the deposition of airborne PFAS from industrial and urban activities (Ismail et al., 2023). In densely populated areas, road dust can be a significant reservoir for PFAS, especially where urban infrastructure and heavy traffic intersect (Ghisi et al., 2019). The contamination due to road dust is particularly concerning in states like Uttar Pradesh and Tamil Nadu, where the population density amplifies exposure risks. The resuspension of contaminated road dust during dry seasons or construction activities can lead to inhalation exposure, while rainwater can wash PFAS-laden dust into nearby water bodies, further contributing to the contamination of surface and groundwater (J.L. Domingo and Nadal, 2019). Moreover, as road dust settles on agricultural lands or urban gardens, PFAS may enter the food chain, potentially impacting food safety and human health (Maddela et al., 2022).

4.6. Wildlife and livestock

The bioaccumulation of PFAS in wildlife has become a significant concern, as these substances persist in the environment and accumulate in the tissues of organisms over time (Savoca and Pace, 2021). In India, research on the bioaccumulation of PFAS in aquatic species, such as dolphins, fish, and shrimp, has revealed alarming concentrations in critical ecosystems like the Ganges River. In this region, concentrations of PFAS in biota have been measured at levels ranging from 0.093 ng/g to 84 ng/g wet weight (ww) (G. Koulini et al., 2024), indicating that PFAS enter the aquatic food chain at multiple trophic levels . The presence of PFAS in top predators such as dolphins suggests that these chemicals are being biomagnified, as organisms higher up in the food chain accumulate higher concentrations of PFAS from their prey (Androulakakis et al., 2022). For example, Houde et al. (2005) reported that PFOS concentrations in bottlenose dolphins reached 1500 – 3000 ng/g wet weight, while concentrations in prey species, such as fish and shrimp, ranged between 150 – 300 ng/g and 40 – 80 ng/g, respectively

(Houde et al., 2006). This indicates a tenfold increase across trophic levels due to biomagnification. PFAS contamination in aquatic species is particularly concerning in regions where fishing is central to local economies and diets (Ahrens, 2011). The bioaccumulation of PFAS in fish and shrimp can potentially affect human populations through dietary exposure. For example, communities relying on fish from the Ganges River or other contaminated water bodies are at risk of ingesting PFAS-contaminated seafood, which can lead to long-term health effects.

The contamination of terrestrial animals has also been documented. In Chennai, pigs raised in areas close to industrial and urban regions have been found to have PFOS and PFOA concentrations of up to 200 ng/g ww (G.V. Koulini and Nambi, 2024), likely stemming from the ingestion of contaminated feed, water, or soil, and raises concerns about human exposure through the consumption of pork (G. Koulini and Nambi, 2024). Livestock raised near contaminated water sources or on farmland irrigated with PFAS-laden water or biosolids can become significant pathways for human exposure, especially in rural and semi-urban areas (Ross et al., 2022). The accumulation of PFAS in biota poses risks to the organisms and has broader ecological implications (Van der Schyff et al., 2020). Contaminated species may experience reproductive, developmental, and immune system effects, which can disrupt entire ecosystems (McCarthy et al., 2017). Moreover, the persistent nature of PFAS means that these chemicals remain in the environment long after their initial release, continuously affecting wildlife and, by extension, human populations.

4.7. Human exposure to PFAS

Human exposure to PFAS in India is a growing concern, as studies have revealed detectable levels of PFAS in human tissues, including serum and breast milk (India-Aldana et al., 2023; Tao et al., 2008). In Chennai and Coimbatore, serum samples from the local population showed concentrations of PFOS and PFOA below 3 ng/mL (G. Jha et al., 2021), which, although relatively low compared to typical global averages (5 – 15 ng/mL for PFOA and 3 – 20 ng/mL for PFOS), still poses a risk due to the cumulative nature of PFAS exposure. The presence of these chemicals in human blood suggests chronic exposure through multiple pathways, including consuming contaminated water and food and contact with PFAS-laden consumer products (Cronin, 2022). Perhaps more concerning is the detection of PFAS in breast milk (Tao et al., 2008), as this indicates direct exposure to vulnerable infants. Studies conducted in Chennai and Kolkata have found perfluorobutane sulfonic Acid (PFBS), perfluorohexanesulfonic acid (PFHxS), and PFOA in breast milk samples, with concentrations ranging from 1.7 to 335 pg/mL. These findings are alarming, as infants are more susceptible to the harmful effects of PFAS, which include developmental delays, immune system suppression, and potential endocrine disruption (Solan et al., 2023; Ding et al., 2020). Breastfeeding, while critical for infant health, can become a pathway for PFAS exposure when the mother's body has accumulated these substances through environmental or dietary routes (J.L. Domingo and Nadal, 2019).

Human exposure to PFAS occurs through different means, with contaminated drinking water being a primary source (Panieri et al., 2022). In regions where PFAS have been detected in groundwater and surface water, such as Tamil Nadu, Gujarat, and West Bengal (Yeung et al., 2009), the population is at risk of ingesting these chemicals daily. The contamination of drinking water systems, combined with using PFAS-containing products like non-stick cookware, water-repellent clothing, and food packaging, contributes to continuous low-level exposure (Wahlström et al., 2021). Dietary intake is another significant pathway, particularly in regions where contaminated fish, livestock, or crops are consumed (G. Jha et al., 2021; Haukås et al., 2007). For example, communities that rely on seafood from the Ganges River are likely to ingest PFAS through contaminated fish and shrimp.

Similarly, agricultural products irrigated with PFAS-contaminated water or fertilised with biosolids can introduce these chemicals into the food supply (Fenton et al., 2021; Ghisi et al., 2019). Given the long half-lives of PFAS in the human body, even low-level exposure over time can lead to bioaccumulation and increased health risks (Cao and Ng, 2021). Human exposure to PFAS has been linked to a range of adverse health effects, including increased cholesterol levels, thyroid dysfunction, liver damage, and an increased risk of certain cancers (Wang et al., 2017). The state-wide environmental occurrence and exposure patterns discussed in this section provide the empirical basis for understanding PFAS dynamics in the environment. Section 5 builds on this by discussing the fate and transport behavior of PFAS in Indian environmental systems, while Section 6 outlines the predictive modeling framework used to simulate their long-term movement and associated exposure risks.

5. Environmental fate and transport of PFAS

Understanding the fate and transport of PFAS is crucial for predicting their long-term environmental impact and developing effective remediation strategies. Their persistence and ability to transport through various environmental media has led to widespread contamination in water, soil, air, and biological systems (Shahsavari et al., 2021). In India, industrial and agricultural practices contribute significantly to the spread of PFAS, affecting ecosystems and public health. PFAS can also undergo long-range atmospheric transport, depositing in regions far from the point of release, making them a global environmental problem (Cousins et al., 2016). Fig. 3 comprehensively depicts PFAS movement through environmental media, emphasizing surface and groundwater pathways. The PFAS contamination was categorized into surface water pathways, encompassing transport via rivers, lakes, and sediments, and groundwater pathways, highlighting subsurface processes such as infiltration and soil adsorption. These pathways were further linked to their ecological impacts, including bioaccumulation in aquatic and terrestrial ecosystems. This underscores critical intervention points for monitoring, regulatory measures, and remediation strategies, aiming to mitigate PFAS contamination risks.

5.1. PFAS mobility in water

PFAS are highly water-soluble, which makes aquatic systems one of the primary pathways for their transport (Li et al., 2020). Once released into surface water bodies such as rivers, lakes, and oceans, PFAS can travel long distances from their sources, contaminating areas far removed from industrial, urban, or agricultural sites (Meegoda et al., 2020). In India, the Ganges River is a major transport pathway for PFAS (Yeung et al., 2009). Contaminants originating from municipal and industrial WWTP effluents and agricultural run-off are carried downstream, affecting ecosystems and communities reliant on the river for drinking water and irrigation (Ding et al., 2020).

The hydrophobic and hydrophilic nature of PFAS plays a crucial role in their transport within water systems (Ahrens et al., 2009). Short-chain PFAS tend to remain in the water phase, whereas long-chain PFAS, such as PFOS and PFOA, have a higher tendency to bind to organic particles and sediments (Kucharzyk et al., 2017). This can lead to the accumulation of long-chain PFAS in riverbeds and wetlands, such as the Sundarbans (Corsolini et al., 2012), where PFOS and PFOA have been detected in sediment samples and can act as reservoirs, slowly releasing PFAS back into the water, especially during natural events like flooding or anthropogenic activities such as dredging. In states like Gujarat and Tamil Nadu, industrial discharges containing PFAS have been shown to contaminate large water bodies like the Sabarmati and Cooum Rivers, respectively (Mohapatra and Basu, 2023). This mobility enables PFAS to infiltrate groundwater systems, a crucial drinking water source for many communities (Bansal et al., 2022). As PFAS persist in surface and groundwater systems, they accumulate in aquatic organisms, affecting the entire food chain.

In addition to surface water transport, PFAS can migrate through the

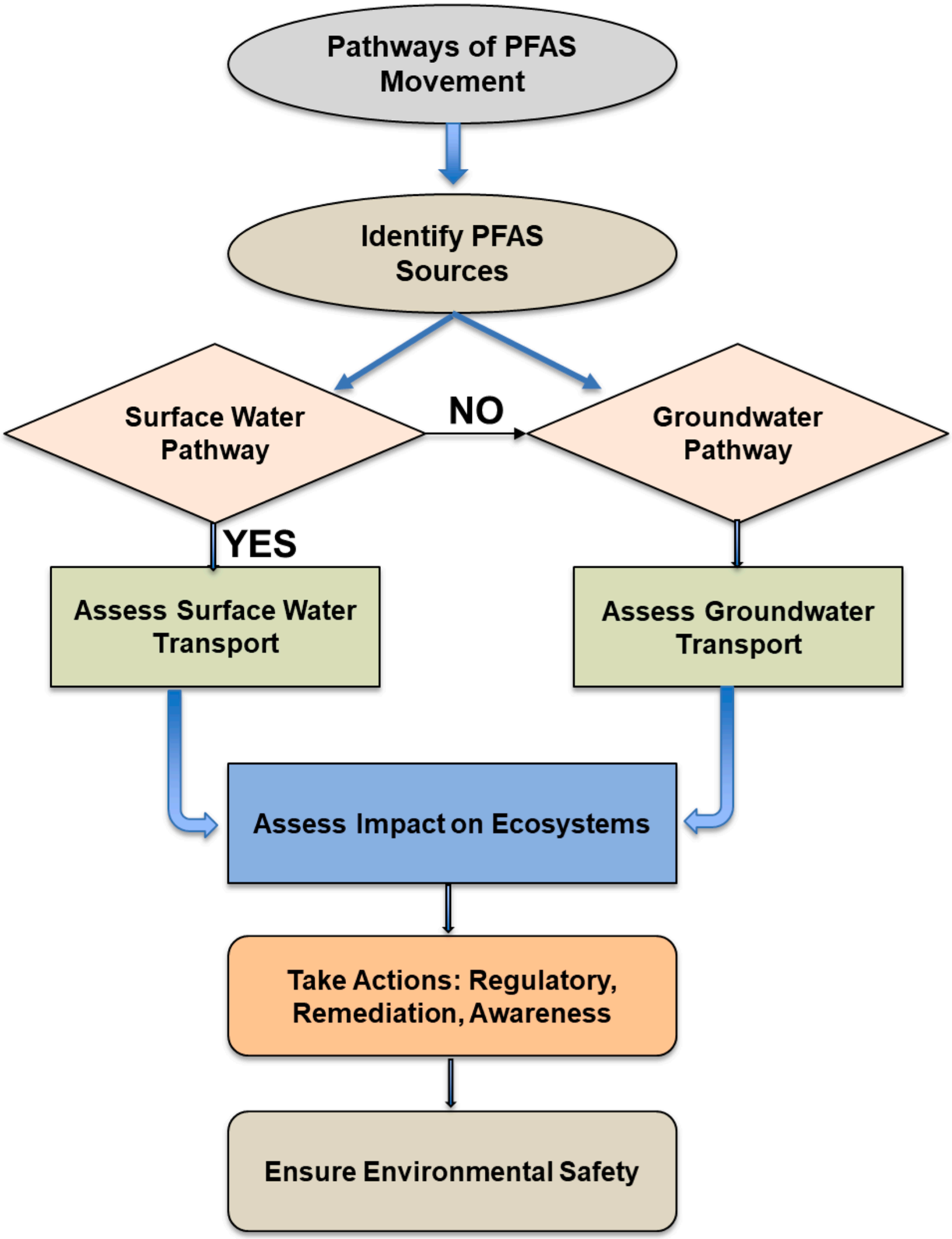

Fig. 3. PFAS pathways into the aquatic environment through surface water and groundwater and environmental mitigation framework.

soil and into groundwater systems, where they can persist for extended periods due to their resistance to natural degradation processes (Sörengård et al., 2022). Groundwater is a particularly critical issue in India, as it is a primary drinking water source for a large portion of the population, especially in rural areas (More et al., 2022; Gautam et al., 2017). Several factors, including the chemical structure of the PFAS, the type of soil, and environmental conditions, such as temperature and pH, influence PFAS transport in the soil (Pereira et al., 2018). The short-chain PFASs are mobile, and Long-chain PFAS, on the other hand, tend to bind to soil particles, reducing their mobility but leading to long-term contamination in soil (Ahrens et al., 2023).

This phenomenon has been observed in regions like Uttar Pradesh, where PFAS from industrial sites and landfills have migrated through the soil into the groundwater, posing significant risks to local water supplies (Yamazaki et al., 2023). In Uttar Pradesh, tannery discharges into the Ganges River have led to the downstream migration of PFAS, affecting both the river ecosystem and adjacent agricultural lands (Garg et al., 2020). PFAS can enter rivers through direct industrial effluent discharge, agricultural run-off, and leaching from contaminated soils. In agriculture, biosolids are applied as fertilisers, and PFAS can leach from the soil into groundwater systems, further spreading contamination (Shahsavari et al., 2021). Using contaminated groundwater for irrigation exacerbates this issue, as PFAS can be reintroduced into the soil and crop systems, leading to widespread contamination of land and water resources (Ge et al., 2017). West Bengal and Punjab are regions where PFAS contamination in groundwater has been linked to agricultural practices involving PFAS-laden biosolids (K. Binu et al., 2022).

5.2. PFAS transport in the atmosphere

PFAS are also subject to atmospheric transport, particularly volatile precursor compounds such as FTOHs and perfluoroalkyl sulfonamides (FASAs), which can travel long distances through the air before degrading into stable PFAS like PFCAs and PFSAs (Solan et al., 2023). These volatile compounds are released into the atmosphere from industrial sites, WWTPs, landfills, and the volatilisation of PFAS-contaminated water bodies (D'Ambro et al., 2021). Studies have detected PFAS in atmospheric samples across major urban areas in India, including Delhi, Mumbai, and Chennai (G. Koulini et al., 2024). The atmospheric transport of PFAS plays a critical role in spreading contamination across vast regions, including remote areas far from the sources of pollution. Once deposited through dry or wet deposition, PFAS can enter terrestrial and aquatic ecosystems, where they persist and bioaccumulate (Brusseau, 2023). Atmospheric transport also contributes to the global spread of PFAS, as these compounds can cross national boundaries and contaminate regions far from their origin (Ng et al., 2021). In Howrah and Kolkata, air samples have shown PFAS concentrations as high as 820 pg/m^3 (Kanjiyangat, 2023), indicating significant atmospheric contamination and subsequent deposition onto urban and rural environments. In Assam and Karnataka, industrial areas near airports have shown signs of PFAS contamination due to the use of firefighting foams, which can evaporate and disperse into the air (Sharma et al., 2016). These volatile compounds can also deposit into nearby soil or water bodies, contributing to secondary contamination (Holt, 2000).

5.3. PFAS fate in biota

Bioaccumulation and Biomagnification have a solid tendency to bioaccumulate in the tissues of living organisms, particularly in aquatic ecosystems (Burkhard and Votava, 2023). PFAS tend to bind to proteins in organisms rather than accumulating in fatty tissues, as is common with many other persistent organic pollutants (Khan et al., 2023). This bioaccumulative property means that PFAS can concentrate in fish, livestock, and even humans over time, posing significant health risks (Xing et al., 2023). This process is particularly prevalent in aquatic ecosystems, where PFAS enter the food web, starting from plankton and eventually making their way up the food chain to larger fish, marine mammals, and humans (Lewis et al., 2022). In India, bioaccumulation of PFAS has been observed in fish, shrimp, and dolphins from the Ganges River and the Sundarban wetlands, where concentrations of PFAS in biota have been reported as high as 83.9 ng/g wet weight (ww) (Sharma et al., 2016). This is a significant concern for communities that rely on food, as consuming contaminated seafood can lead to long-term exposure to PFAS and associated health risks.

On the other hand, biomagnification refers to the process by which PFAS concentrations increase as they move up the food chain (Cheng et al., 2022). Top predators, such as dolphins and large fish, tend to have the highest concentrations of PFAS due to their consumption of smaller contaminated organisms (Androulakakis et al., 2022). This phenomenon amplifies the risks associated with PFAS exposure for both wildlife and humans, as the chemicals accumulate to higher levels in species that humans consume.

6. Modelling the fate and transport of PFAS in the surface water system

6.1. Model framework and scope

To understand the spread and long-term behaviour of PFAS in surface water systems, a comprehensive modelling framework was developed to simulate their transport through rivers, groundwater, and coastal regions. This modelling section investigates the fate and transport of these key PFAS compounds across selected Indian states- Gujarat, Tamil Nadu, Maharashtra, Uttar Pradesh, West Bengal, Andhra Pradesh, Punjab, and Rajasthan over 30 years (2024 – 2054), focusing on water systems as the primary medium for contamination. Given the limited availability of research on PFAS contamination in India, the modelling relied on an extensive literature review to extract data specific to PFHxS, PFOS, PFOA and PFNA. These compounds were selected due to their prevalence in environmental matrices and the availability of concentration data across the few included states. The properties of these PFAS compounds, including their sorption coefficients, degradation rates, and initial concentrations, were incorporated into the modelling framework to enhance the accuracy and specificity of the results.

The model simulates initial and projected PFHxS, PFOS, PFOA and PFNA concentrations, incorporating parameters such as water flow rates, groundwater recharge, atmospheric deposition, sorption to soils, and degradation rates. Using a mass-balance equation, the model accounts for advection (the movement of PFAS with water flow), diffusion, sorption, and degradation to predict the spread and accumulation of these compounds over time. While this study provides a detailed model of PFAS contamination, the limited availability of regional data posed challenges in achieving absolute accuracy. States such as Assam and Karnataka were considered for inclusion; however, due to insufficient data on specific PFAS compounds, a reliable simulation of PFAS spread in these regions was not feasible at this stage.

6.2. Modelling approach and limitations

6.2.1. Steady-state mass-balance fate and transport model

The model has assumed steady-state flow conditions ($Q_{in} = Q_{out}$), following first-order degradation and sorption with uniform environmental conditions throughout the simulation period. The fate and transport model of four PFAS (PFHxS, PFOS, PFOA and PFNA) is based on the following mass balance equation, which tracks the change in PFAS concentration over time:

$$\frac{dC}{dt} = Input - Output + Advection + Diffusion - Sorption - Degradation + Atmospheric\ Deposition + Recharge \tag{1}$$

Where C is the PFAS concentration (ng/L), input refers to PFAS entering the system via sources (industrial effluents, wastewater treatment plants, atmospheric deposition, etc.), output refers to PFAS leaving the system via losses (e.g., outflow from a river or groundwater flow out), advection accounts for PFAS transport by bulk water movement (e.g., rivers), diffusion refers to the spread due to concentration gradients, sorption refers to adsorption onto soil and sediment particles, and degradation applies to PFAS precursors, which degrade into stable PFAS compounds, atmospheric deposition refers to PFAS deposited from the atmosphere and recharge refers to the PFAS entering groundwater system. This basic mass balance equation for each environmental compartment: surface water, groundwater, soil, and air, and specific transport mechanisms are detailed in Eqs. (2) – 13 as follows:

6.2.1.1. Water flow rate (advection). The advection (Wallis et al., 2022) is given by:

$$\text{Advection} = v\frac{dC}{dx} \tag{2}$$

where v is the flow velocity (m/s). $\frac{dC}{dx}$ is the concentration gradient in the flow direction.

6.2.1.2. Groundwater recharge rate. The recharge rate (Healy, 2010) is given by:

$$\text{Recharge} = R.\theta \tag{3}$$

where R is the recharge rate (m/year), and θ is the porosity of the aquifer.

6.2.1.3. PFAS sorption (soil and sediments). The sorption of PFAS into soils and sediments (Umeh et al., 2023) is modelled using the following equation:

$$\text{Sorption loss} = k_s.C_o \tag{4}$$

where k_s is the sorption coefficient (L/kg), representing the quantity of PFAS retained in the soils or sediments and C_o is the initial concentration (ng/L).

6.2.1.4. Degradation rate (precursors). The degradation rate of the precursors (Umeh et al., 2023) is given by:

$$\text{Degradation rate} = -k_d.C_o \tag{5}$$

where k_d is the degradation rate constant (1/year) for PFAS precursor, leading to the formation of stable PFAS and C_o is the initial concentration (ng/L)

6.2.1.5. Atmospheric deposition. PFAS accumulation due to atmospheric deposition (D'Ambro et al., 2023), especially during monsoonal rains, is calculated using:

$$\text{Atmospheric Input} = P_{rain}.D_{atm} \tag{6}$$

where P_{rain} is the rainfall (m. year), and D_{atm} is the atmospheric deposition rate (ng/m^2/year).

6.2.1.6. Wastewater treatment plant contributions

$$\text{WWTP input} = \frac{C_{wwtp}\ .\ Q_{wwtp}}{V} \tag{7}$$

Where, $C_{wwtp.}$ Is the PFAS concentration in WWTP effluent (ng/L), Q_{wwtp} is the WWTP discharge (m^3/year), V is the volume of the receiving body (m^3).

6.2.1.7. Partition coefficient. The partition coefficient (Hidalgo and Mora-Diez, 2016) for organic carbon:

$$\text{Atmospheric Input} = K_{oc}.C_{organic\ carbon} \tag{8}$$

where, K_{oc} is the partition coefficient for organic carbon (L/kg), and $C_{organic\ carbon}$ is the concentration of organic matter in the soil.

6.2.1.8. Groundwater recharge. Groundwater recharge impacts are modelled and incorporated (Gautam et al., 2018) with a partition coefficient to simulate PFAS movement (Healy, 2010) into groundwater systems:

$$\text{Recharge Effect} = R.K_{oc} \tag{9}$$

6.2.1.9. PFAS accumulation model (surface water). The concentration of PFAS in surface water after 30 years can be calculated by combining Eqs. (1)–8 and is given by the following equation:

$$C = C_o\ (1 + v.t.365) + D_{atm}t - (k_sC_o) - (k_dC_o) + (RK_{oc}) + \frac{C_{wwtp}\ .\ Q_{wwtp}}{V} \tag{10}$$

where, C_o is the initial concentration (ng/L), v is the water flow rate (m^3/s), t is the time (years), D_{atm} is atmospheric deposition (ng/m^2/year), k_s is the sorption coefficient (1/year), k_d is the degradation rate constant (1/year), R is the groundwater recharge (m/year), and K_{oc} is the partition coefficient for organic carbon (L/kg)

6.2.2. Bioaccumulation and exposure equations

6.2.2.1. Bioaccumulation. The general equation for bioaccumulation is given by:

$$C_o = BAF\ .\ C_w \tag{11}$$

where, C_o is the concentration of PFAS in the organism (µg/kg), C_w is the concentration of PFAS in the water (µg/L), and BAF is the bioaccumulation factor (dimensionless) specific to species or ecosystem.

6.2.2.2. Long-term exposure. The human intake through dietary exposure, particularly from fish consumption (Mozaffarian and Rimm, 2006), was calculated using the following equation:

$$Human\ intake = C_o\ .\ D_i \tag{12}$$

where human intake is the amount of PFAS ingested by humans via food consumption (µg/day), D_i is the dietary intake rate (kg/person/year), C_o is the PFAS concentration in the consumed organism (µg/kg).

6.2.2.3. Long-term exposure. To calculate long-term PFAS exposure, CDI is determined based on PFAS intake from drinking water, food, and air over set periods (Brown et al., 2020). The formula for the CDI is as follows:

$$CDI = \frac{Concentration\ (C).IngestionRate\ (IR).ExposureDuration\ (ED).Exposure\ Frequency\ (EF)}{Body\ Weight\ (BW).AverageTime\ (AT)} \tag{13}$$

where C is the concentration of PFAS in water (µg/L), IR is the ingestion rate (L/day or kg/day for food), ED is the exposure duration (years), EF is the exposure frequency (days/year), BW is the average body weight of the individual (kg), and AT is the averaging time (days/year).

6.3. Parameter sources, assumptions, and limitations

Refer to Table 3 and Table S1 in SI for all parameter values. Model inputs are either India-specific (where available) or extrapolated from international literature. The model assumes steady-state flow conditions and uniform environmental parameters throughout the 30-year simulation. WWTP effluent concentrations and atmospheric deposition rates are derived from international studies and scaled to fit Indian industrial contexts. While the model captures key transport mechanisms such as advection, sorption, degradation, and deposition, it excludes vertical stratification, transformation intermediates, and non-aqueous phase dynamics. Though necessary due to data limitations, these simplifications may influence predictive precision, underscoring the need for localized, high-resolution environmental datasets in future modeling efforts.

Table 3
Model parameters and inputs for PFAS fate and transport modelling.

Parameter	Symbol	Unit	PFOS	PFOA	PFHxS	PFNA	Reference
Initial concentrations	C_o	µg/L	Varies by state (Table S1 in SI)				(Death et al., 2021; Möller et al., 2010; John et al., 2022; Ahrens, 2011; McCleaf et al., 2017)
Degradation rate	k_d	1/year	0.0001	0.00015	0.0001	0.0002	(Sörengård et al., 2022; Wickham and Shriver, 2021)
Sorption rate	k_s	1/year	0.05	0.03	0.04	0.02	(Ng et al., 2021)
Partition coefficient	K_{oc}	L/kg	2.0	1.6	1.3	1.8	(Reinikainen et al., 2024)
Inflow/outflow rate	Q_{in}, Q_{out}	m^3/year	3.15×10^9				(Brunn et al., 2023)
Atmospheric deposition	D_{atm}	µg/L/year	0.01				(Jala et al., 2023)
Groundwater recharge	R	m/year	0.02				(Death et al., 2021; Peshoria et al., 2020)
Monsoon influence	R	m/day	0.02				(Gagliano et al., 2020)
Velocity of water	v	m.day	0.05				(Gagliano et al., 2020)
WWTP concentration	$C_{wwtp.}$	µg/L	1.5	1.2	0.9	0.8	(Jia et al., 2023; Banwell et al., 2021; Singh et al., 2023; Sharma et al., 2024; Hariharan et al., 2023)
WWTP flowrate	Q_{wwtp}	m^3/year	1.825×10^9				(Hariharan et al., 2023; G. Jha et al., 2021)

Note: Initial concentrations are drawn from empirical data presented in Table S1 (Supplementary Information).

7. Results and interpretation of PFAS transport, bioaccumulation, and exposure modeling

7.1. Fate and transport model

The model incorporates key parameters to simulate PFAS (PFHxS, PFOS, PFOA and PFNA) dynamics in surface water systems, considering contributions from both point sources (e.g., WWTP discharges) and diffuse sources (e.g., atmospheric deposition). However, specific data on PFAS concentrations in WWTP discharges and atmospheric deposition rates in India are currently unavailable. The model relied on estimates from international studies and global trends to address this gap (Wallis et al., 2022; Ng and Hungerbühler, 2014; Zeng et al., 2021; Eklund; Liang et al., 2022). For point sources such as WWTPs, typical PFAS discharge concentrations were extrapolated from global studies conducted in industrial regions (Cantoni et al., 2024; Sun et al., 2024; Zhang et al., 2021; Baresel et al., 2023). These values were scaled to align with known industrial activities in states like Tamil Nadu and Gujarat.

Similarly, atmospheric deposition rates were derived from global data (Faust, 2023; Ge et al., 2017; Li et al., 2011; Venkatram et al., 2013), adjusting to India's monsoonal climate, significantly influencing PFAS deposition patterns. Chemical properties, such as water solubility, sorption behaviour (binding to soil particles), and degradation rates, were incorporated to simulate PFAS behaviour in the environment (Table 3). Water flow rates for major rivers and groundwater recharge rates in contaminated regions were considered to simulate PFAS transport in hydrologically active areas (Table 3). The selected parameter values represent upper-bound estimates derived from literature and environmental monitoring studies in industrial regions of India and globally, as shown in Table 3. These simulate long-term PFAS transport under worst-case, yet realistic, environmental conditions. The initial PFAS concentrations for key Indian states were drawn from previous studies, summarised in Table S1 in SI. The model results, representing PFAS contamination after 30 years (2024 – 2054), were compared against initial concentrations to assess the extent of contamination. The simulation conducted over 30 years (2024 – 2054) revealed a sharp upward trend in PFAS concentrations across industrialized states, with levels projected to exceed safe drinking water limits (Table 4 and Fig. 4). This increase is primarily driven by continuous industrial discharges, the inherent stability and resistance of PFAS compounds to degradation, and regional environmental factors that accelerate PFAS transport (Sun et al., 2024). The impact of these factors varied depending on the intensity of industrial activity, regulatory measures, and environmental conditions.

Table 4
Simulated PFAS concentrations in surface water at selected locations over 30 years (2024 – 2054).

Location	Predicted PFOS Concentration (µg/L) After 5 Years	Predicted PFOS Concentration (µg/L) After 10 Years	Predicted PFOS Concentration (µg/L) After 15 Years	Predicted PFOS Concentration (µg/L) After 30 Years	Predicted PFOA Concentration (µg/L) After 5 Years	Predicted PFOA Concentration (µg/L) After 10 Years	Predicted PFOA Concentration (µg/L) After 15 Years	Predicted PFOA Concentration (µg/L) After 30 Years	Predicted PFHxS Concentration (µg/L) After 5 Years	Predicted PFHxS Concentration (µg/L) After 10 Years	Predicted PFHxS Concentration (µg/L) After 15 Years	Predicted PFHxS Concentration (µg/L) After 30 Years	Predicted PFNA Concentration (µg/L) After 5 Years	Predicted PFNA Concentration (µg/L) After 10 Years	Predicted PFNA Concentration (µg/L) After 15 Years	Predicted PFNA Concentration (µg/L) After 30 Years	Total PFAS Concentration (µg/L) After 30 Years	[a]Risk Factor After 30 Years
Gujarat (Industrial Zone)	0.186	0.223	0.261	0.382	0.189	0.229	0.27	0.395	0.193	0.236	0.279	0.411	0.187	0.225	0.264	0.387	1.576	High
Tamil Nadu (Textile Hub)	0.14	0.182	0.224	0.355	0.143	0.186	0.23	0.364	0.145	0.19	0.236	0.374	0.141	0.183	0.226	0.358	1.451	High
Maharashtra (Tannery Area)	0.104	0.149	0.194	0.333	0.106	0.152	0.198	0.338	0.107	0.154	0.202	0.344	0.105	0.15	0.196	0.335	1.35	High
Uttar Pradesh	0.104	0.149	0.194	0.333	0.106	0.152	0.198	0.338	0.107	0.154	0.202	0.344	0.105	0.15	0.196	0.335	1.35	High
West Bengal	0.095	0.141	0.187	0.327	0.096	0.143	0.19	0.332	0.098	0.145	0.193	0.337	0.096	0.142	0.188	0.329	1.325	High
Andhra Pradesh	0.131	0.174	0.217	0.349	0.133	0.177	0.222	0.357	0.136	0.181	0.227	0.367	0.132	0.175	0.219	0.352	1.426	High
Punjab	0.177	0.215	0.254	0.377	0.18	0.22	0.262	0.389	0.183	0.227	0.27	0.404	0.178	0.217	0.257	0.381	1.551	High
Rajasthan	0.113	0.157	0.202	0.338	0.115	0.16	0.206	0.345	0.117	0.163	0.21	0.352	0.114	0.158	0.203	0.341	1.375	High

a Risk level is categorized based on predicted PFAS concentrations in groundwater relative to established safety thresholds for drinking water, such as those set by the US EPA and EU. High Risk: Predicted PFAS concentrations exceed the US EPA's maximum contaminant level (MCL) for PFOA and PFOS (4 ng/L) by more than 10 times, indicating significant potential health and environmental risks.

[a] Risk level is categorized based on predicted PFAS concentrations in groundwater relative to established safety thresholds for drinking water, such as those set by the US EPA and EU. High Risk: Predicted PFAS concentrations exceed the US EPA's maximum contaminant level (MCL) for PFOA and PFOS (4 ng/L) by >10 times, indicating significant potential health and environmental risks.

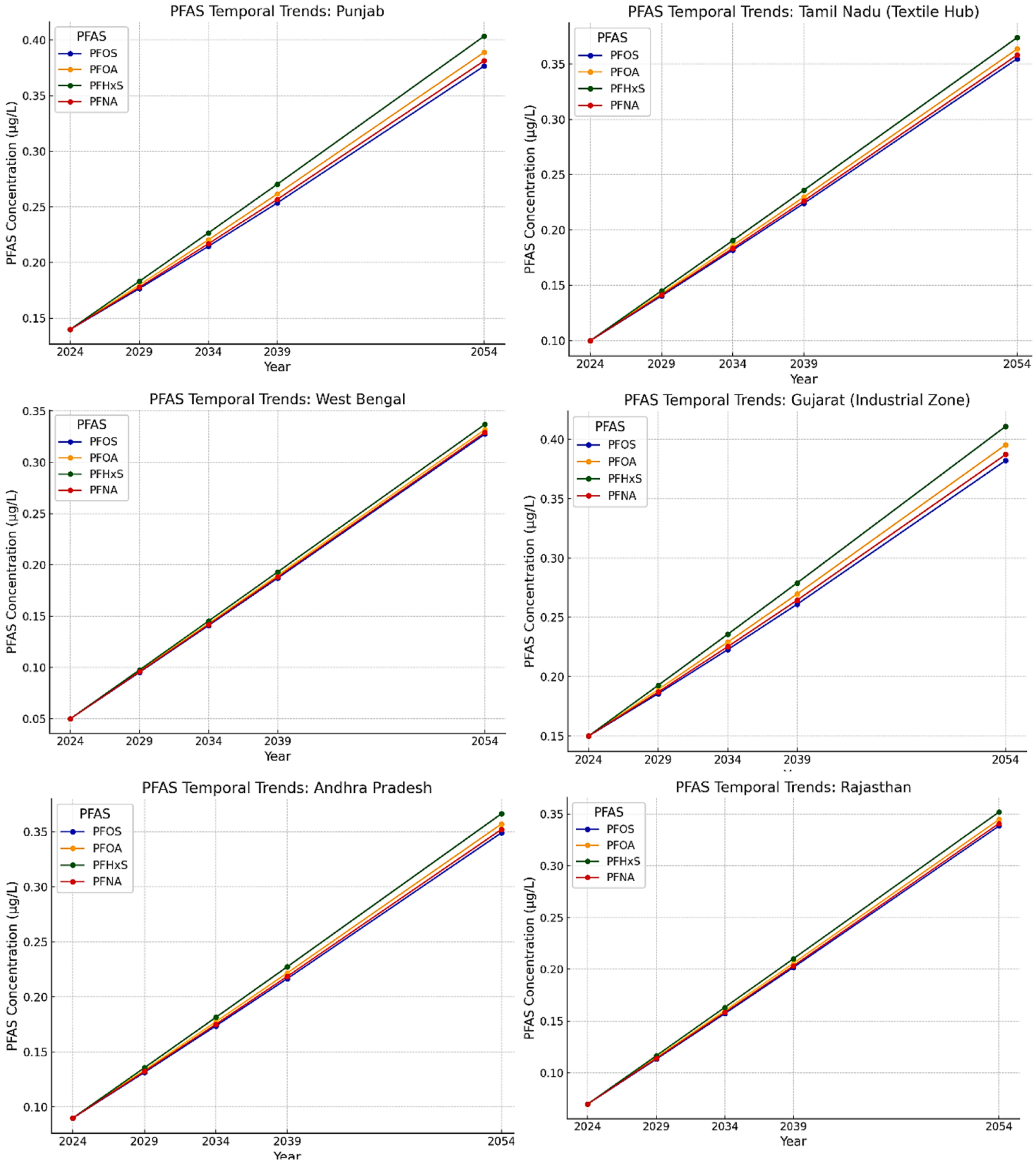

Fig. 4. Predicted temporal trends of PFAS concentrations (PFHxS, PFOS, PFOA and PFNA) in surface water near PFAS sources across various states (2024 – 2054), assuming continued emissions without implementation of treatment techniques.

At the location in Gujarat, specifically in the industrial hubs of Vapi and Ankleshwar (IPEN, 2019), PFOS concentrations are projected to increase from 0.19 µg/L (2029) to 0.38 µg/L (2054), while PFOA concentrations rise from 0.19 µg/L (2029) to 0.40 µg/L (2054). Similarly, PFHxS levels increase to 0.41 µg/L, and PFNA levels rise to 0.39 µg/L over the same period. These trends are driven by Gujarat's extensive chemical and polymer manufacturing industries at Vapi and Ankleshwar (Mohapatra and Basu, 2023), contributing significantly to PFAS accumulation. The state's limited soil adsorption capacity also facilitates the migration of these compounds into surface and groundwater (Kanjiyangat, 2023). Global parallels can be drawn to manufacturing hotspots in Daegu, South Korea, where similar industrial discharges have led to persistently high PFAS concentrations in water systems (Kim et al., 2007; Choi et al., 2021).

Similarly, in Tamil Nadu, specifically in textile hubs like Tiruppur and industrial areas (G. Sunantha and Vasudevan, 2016) near Chennai, the concentration of PFOS is predicted to increase from 0.140 µg/L (2029) to 0.3655 µg/L (2054), with PFOA levels rising from 0.143 µg/L to 0.364 µg/L over the same period. PFHxS and PFNA concentrations show similar trends, reaching 0.374 µg/L and 0.3658 µg/L, respectively. The textile industry, a dominant sector in Tamil Nadu, significantly contributes to PFAS contamination due to its heavy reliance on stain-resistant and water-repellent coatings. Monsoon rains exacerbate this issue by enabling run-off and leaching from industrial discharge points into surrounding water systems, accelerating PFAS migration into groundwater (Selladurai et al.). These trends mirror those observed in

Bangladesh, where textile zones contribute heavily to PFAS contamination in surface and groundwater systems (Alam and Chen, 2024).

Similarly, in Maharashtra, specifically in the tannery zones of Thane and industrial belts near Mumbai (Singare and Jagtap, 2018), PFOS concentrations are likely to rise from 0.104 μg/L (2029) to 0.333 μg/L (2054), while PFOA levels increase to 0.3438 μg/L over the same period. PFHxS concentrations are projected to reach 0.344 μg/L and PFNA to 0.3435 μg/L by 2054. PFAS is commonly used in leather treatment and chemical production, leading to continuous PFAS loading in wastewater (Vesce et al., 2022). The persistence of PFAS in Maharashtra's soils, combined with inadequate treatment facilities, allows for sustained contamination of groundwater resources over time. Similar contamination trends have been observed in regions such as Tuscany, Italy, where leather industries contribute significantly to PFAS pollution in water resources (Bonato et al., 2020).

In Uttar Pradesh, specifically in Kanpur's industrial zones along the Ganges River (Singh et al., 2024), PFOS concentrations are projected to increase from 0.104 μg/L (2029) to 0.333 μg/L (2054), with PFOA, PFHxS, and PFNA concentrations reaching 0.3438 μg/L, 0.344 μg/L, and 0.3435 μg/L, respectively. The combined impact of untreated industrial wastewater and agricultural run-off contributes to this contamination. PFAS-containing biosolids from industrial and agricultural activities are a key source, similar to observations in the U.S., where biosolid applications in agriculture have been linked to persistent PFAS contamination (Christensen et al., 2022; Pepper et al., 2021). This combination poses a dual threat to groundwater and surface water quality in a state heavily reliant on these resources for agriculture and drinking water.

In West Bengal, specifically in the Hooghly River basin and industrial zones near Howrah (Philip et al., 2018), PFOS levels are expected to increase from 0.095 μg/L (2029) to 0.3327 μg/L (2054), while PFOA, PFHxS, and PFNA concentrations rise to 0.332 μg/L, 0.3437 μg/L, and 0.3329 μg/L, respectively. The agricultural use of PFAS-containing products plays a significant role in this contamination (Singh et al., 2024). Agrochemical run-off and untreated industrial discharges mirror trends observed in Brazil's agricultural zones, where PFAS contamination from agrochemical use has severely impacted water resources (Andrade Rivas, 2023).

In Andhra Pradesh, specifically in coastal regions near Vishakhapatnam and industrial zones in Guntur (Arora et al., 2023), PFOS concentrations are projected to increase from 0.131 μg/L (2029) to 0.3549 μg/L (2054), with PFOA, PFHxS, and PFNA concentrations rising to 0.3657 μg/L, 0.3767 μg/L, and 0.352 μg/L, respectively. Industrial discharges from small and medium enterprises and run-off from agrochemical use are major contributors to this rise. Similar trends have been observed in rural China, where industrial and agricultural discharges contribute to persistent PFAS contamination (Wang et al., 2024). In Punjab, particularly in Ludhiana's agro-industrial belt, and Rajasthan, specifically near Jaipur's industrial zones (Sackaria and Elango, 2020), industrial and agricultural practices contribute significantly to PFAS contamination. Punjab is projected to reach 0.381 μg/L and Rajasthan to 0.341 μg/L for PFNA concentrations by 2054. In Punjab, PFOS, PFOA, and PFHxS are projected to reach 0.3877 μg/L, 0.3989 μg/L, and 0.404 μg/L, respectively, reflecting extensive use of agrochemicals and untreated wastewater discharges from industries (Riaz et al., 2023). In Rajasthan, where water scarcity already poses a challenge, PFOS levels rise to 0.34 μg/L, with PFOA, PFHxS, and PFNA concentrations increasing steadily due to persistent industrial discharges and limited natural water dilution. These trends align with contamination patterns in arid regions such as South Africa, where industrial activity compounds water scarcity issues (du Plessis and du Plessis, 2019). These findings underscore the urgent need for intervention to address the sharp rise in individual PFAS concentrations across these Indian states. The primary drivers, persistent industrial discharges, inadequate wastewater treatment, and enhanced PFAS mobility during monsoons, highlight gaps in PFAS-specific regulations within current environmental policies. Mitigation measures should include strict PFAS regulations, adopting advanced treatment technologies in industrial effluents, and routine monitoring of individual PFAS levels in groundwater. Learning from global best practices, such as Sweden's implementation of advanced PFAS regulations and water treatment systems (Baresel et al., 2023), could help mitigate the risks posed by these persistent contaminants in India. Proactive intervention is essential to curb PFAS pollution, as the projected contamination levels pose severe risks to public health, agriculture, and environmental sustainability in states with extensive industrial activities and a heavy reliance on groundwater.

7.1.1. *Statistical analysis of the fate and transport mode*

A detailed statistical analysis was conducted to evaluate the relationship between initial PFAS concentrations and final predicted concentrations over time, focusing on the individual PFAS compounds, PFHxS, PFOS, PFOA and PFNA across the studied states (Section S2.1, SI). The correlation analysis (S2.1.1, Table S2 in SI) demonstrated a strong linear relationship ($p < 0.001$, Pearson correlation) between initial concentrations and final concentrations for each PFAS compound after 30 years for all investigated locations. Pearson correlation coefficients were highest for PFOS (0.98), followed by PFOA (0.96), PFHxS (0.95), and PFNA (0.94). These findings highlight that states with higher initial PFOS and PFOA contamination levels are more strongly associated with elevated long-term concentrations than PFHxS and PFNA. The linear regression analysis (S2.1.2, Table S3 in SI) further supported this trend, indicating that for every theoretical 1 μg/L increase in the initial concentration of PFOS, the final PFOS concentration after 30 years increases by 2.3 μg/L ($R^2 = 0.92$, $p < 0.001$). Similarly, the predicted increases for every theoretical 1 μg/L for PFOA, PFHxS, and PFNA were 2.5 μg/L, 2.1 μg/L, and 2.2 μg/L, respectively, with R^2 values ranging from 0.89 to 0.93. This analysis underscores the strong predictive power (Cohen et al., 2009) of initial PFAS levels on long-term outcomes, with PFOS exhibiting the highest sensitivity to changes in initial concentrations. The ANOVA results (S2.1.3, Table S4 in SI) revealed statistically significant differences in PFAS concentrations between states after 30 years ($p < 0.001$, F-statistic = 16.45) (Cohen et al., 2009). The variance was highest for PFOS and PFOA, particularly in states like Gujarat and Punjab, where industrial discharges and untreated effluents contribute significantly to contamination. In contrast, states with lower industrial activity, such as West Bengal and Maharashtra, exhibited lower variances across all PFAS compounds. These findings emphasize the critical role of initial contamination in determining the long-term fate of individual PFAS compounds. The results also highlight the disproportionate impact on certain states and the need for targeted mitigation strategies to address compound-specific contamination patterns.

7.2. *Modelling the PFAS dynamics in ecosystems: bioaccumulation, exposure, and human health implications*

This section investigates PFAS contamination in selected states of India, focusing on its environmental persistence and public health impacts. It begins by examining bioaccumulation in aquatic and terrestrial ecosystems, emphasizing how PFAS accumulate in organisms and enter food chains, affecting ecosystem health and biodiversity (Lesmeister et al., 2021). The analysis then focuses on PFAS transport and spread from industrial hotspots, where manufacturing and agricultural practices contribute to increased emissions. This includes evaluating source control measures to reduce PFAS dispersion into surrounding environments (Wickersham et al., 2023). The public health implications of PFAS exposure are also addressed, with an emphasis on chronic health risks, including cancers, liver toxicity, and reproductive harm (Wee and Aris, 2023).

Modelling limitations due to data constraints are acknowledged (IPEN, 2019), particularly given the limited PFAS reporting across India. Despite these challenges, the study drew from diverse sources, including environmental assessments, literature, and government reports, to comprehensively analyse PFAS contamination and its impacts. This underscores the need for enhanced monitoring and regulatory frameworks to address PFAS contamination effectively. Increasing community awareness about PFAS risks is crucial for mitigating exposure and safeguarding public health (Berthold et al., 2023). By synthesizing these aspects, this section highlights the complexities of PFAS contamination in India and advocates for a systematic approach to protecting the environment and public health.

7.2.1. Modelling the bioaccumulation of PFAS in fish and human exposure

PFAS are well-known for their environmental persistence, bioaccumulation potential, and ability to biomagnify through the food chain (Ahrens and Bundschuh, 2014). This section primarily explores the bioaccumulation and biomagnification of PFAS in India's aquatic ecosystems, focusing on states with significant industrial and agricultural activities that contribute to PFAS contamination in surface water. Bioaccumulation refers to the accumulation of PFAS compounds in an organism over time, often at a rate faster than elimination, resulting in concentrations much higher than in the surrounding environment. Biomagnification occurs when these concentrations further increase the food chain, posing risks to top-level predators, including humans, especially those reliant on fish or animal products (Christensen et al., 2017). While the terrestrial ecosystem was not explicitly modelled in this study, PFAS exposure through terrestrial pathways such as crop uptake, livestock contamination, and soil leaching remains critical for future research. Agricultural runoff containing PFAS could lead to soil contamination, and bioaccumulation in crops or grazing animals could contribute to human exposure. However, data limitations on PFAS levels in Indian soils and terrestrial biota constrained the scope of this analysis to aquatic systems. This analysis models PFAS (PFHxS, PFOS, PFOA and PFNA) bioaccumulation in selected Indian states: Gujarat, Tamil Nadu, Maharashtra, Uttar Pradesh, West Bengal, Andhra Pradesh, Punjab, and Rajasthan representing diverse industrial, agricultural, and urban environments with varying PFAS exposure levels and dietary patterns. To assess PFAS bioaccumulation, the bioaccumulation factor (BAF) (Ng and Hungerbühler, 2014; Liang et al., 2022; Burkhard, 2021) was used to express the ratio of PFAS concentration in an organism to the concentration in the surrounding environment (e.g., water or soil).

The modelling results for PFAS bioaccumulation and corresponding human intake across different states are summarized in Table 5, which provides a comparative overview of PFAS exposure based on water concentration, BAF, fish consumption rates, and estimated daily human intake. PFAS bioaccumulation in aquatic systems has been extensively studied globally (Valsecchi et al., 2021; Giari et al., 2023; Hoa et al., 2022; Pickard et al., 2022), and similar trends can be expected in Indian aquatic ecosystems. As indicated in the updated Table 5, Tamil Nadu exhibits the highest PFAS bioaccumulation in fish, with PFOS concentrations reaching 1780 μg/kg ww based on a water concentration of 0.355 μg/L and a BAF of 5000, given Tamil Nadu's high fish consumption rate of 23 kg/year (Ahrens and Bundschuh, 2014). Given Tamil Nadu's high fish consumption rate of 23 kg/year (Vieira et al., 2015), the estimated human intake of total PFAS is 177 μg/day, significantly higher than other states. Gujarat follows closely, with PFOS concentrations in fish estimated at 1910 μg/kg ww based on a water concentration of 0.382 μg/L, despite its lower fish consumption rate of 8 kg/year (SHUKLA; Shyam, 2016). Human intake is estimated at 41.9 μg/day, reflecting the high water contamination in this industrialized region (Giari et al., 2023).

In Maharashtra, moderate PFAS contamination levels are observed, with PFOS concentrations reaching 1670 μg/kg ww due to a water concentration of 0.333 μg/L and a BAF of 5000. The fish consumption rate in Maharashtra is 10 kg/year (Das and Janardhanan, 2022), resulting in a daily PFAS intake of 45.6 μg/day (Burkhard, 2021). Similarly, Uttar Pradesh, particularly along the Ganges River, shows PFOS concentrations of 1670 μg/kg ww in fish (Sharma et al., 2016), reflecting water contamination levels of 0.333 μg/L and a BAF of 5000. With an average fish consumption rate of 6 kg/year (Yeung et al., 2009), human PFAS intake is estimated at 27.4 μg/day. West Bengal, where fish consumption is significant at 25 kg/year (K. Binu et al., 2022), exhibits moderate water contamination, with PFOS concentrations of 1640 μg/kg ww in fish (IPEN, 2019). The high fish consumption rate results in a daily human PFAS intake of 112.05 μg/day, underscoring the combined impact of dietary habits and environmental exposure. Similarly, Andhra Pradesh, with a fish consumption rate of 18 kg/year (Shyam and Akhila, 2022), has estimated PFOS concentrations of 1750 μg/kg ww (G. Koulini and Nambi, 2024), resulting in a daily intake of 86.1 μg/day, highlighting significant exposure risks due to both industrial discharges and dietary patterns.

Punjab, with a water PFAS concentration of 0.377 μg/L, exhibits PFOS concentrations of 1885 μg/kg ww in fish. Despite its lower fish

Table 5
Estimated intake of PFAS by humans due to fish consumption[a].

State	[b]PFOS Concentration in Fish (μg/kg ww)	[b]PFOA Concentration in Fish (μg/kg ww)	[b]PFHxS Concentration in Fish (μg/kg ww)	[b]PFNA Concentration in Fish (μg/kg ww)	Total PFAS Concentration in Fish (μg/kg ww)	[c]Fish Consumption (kg/year)	[d]Human Intake of Total PFAS (μg/day)
Gujarat (Industrial Zone)	1910	1780	1640	1360	6690	8.0	147
Tamil Nadu (Textile Hub)	1780	1640	1500	1250	6170	23.0	388
Maharashtra (Tannery Area)	1670	1520	1380	1170	5740	10.0	157
Uttar Pradesh	1670	1520	1380	1170	5740	6.0	94.3
West Bengal	1640	1490	1350	1150	5630	25.0	386
Andhra Pradesh	1750	1610	1470	1230	6060	18.0	298
Punjab	1880	1750	1620	1330	6590	6.0	108
Rajasthan	1690	1550	1410	1190	5850	2.0	32.0

[a] BAF = Bioaccumulation factor of individual PFASs; PFOS (5000), PFOA (4500), PFHxS (4000) and PFNA (3500) in fish tissue to that in water extracted from (G. Koulini and Nambi, 2024; Gobelius et al., 2018; Abunada et al., 2020), accounting for specific PFAS chemical properties and species variations (e.g., lipid content of fish, trophic level). The differences in BAF are due to the varying bioaccumulation potential of different PFAS compounds.

[b] PFAS (PFOS, PFOA, PFHxS and PFNA) Steady-state concentrations (Fish): Estimated PFAS concentrations in fish tissue calculated using BAF and $\sum$ PFAS concentration in water.

[c] Fish consumption was calculated based on average fish consumption rates for each state from literature data (Wang et al., 2017; EPA, 2023).

[d] Human intake was Estimated using the formula: Human Intake = Fish Concentration × Fish Consumption (Normalized to daily intake values in μg/day).

consumption rate of 6 kg/year (Riaz et al., 2023), human intake is estimated at 31.0 μg/day, primarily driven by agro-industrial run-off contributing to elevated water contamination levels (Suthar, 2011). In contrast, Rajasthan shows minimal exposure, with PFOS concentrations in fish of 1690 μg/kg ww based on a water concentration of 0.338 μg/L and a BAF of 5000. Due to its low fish consumption rate of 2 kg/year (Suthar, 2011), human intake is only 9.26 μg/day (Suthar, 2011).

The bioaccumulation model reveals considerable differences in PFAS exposure across these Indian states, influenced by environmental contamination levels and dietary habits. With high fish consumption rates, states like Tamil Nadu, West Bengal, and Andhra Pradesh exhibit elevated PFAS exposure risks, particularly from PFOS and PFOA (Shyam, 2016). Conversely, states like Rajasthan, where fish consumption is minimal, show significantly lower human PFAS intake. These findings highlight the intersection of dietary practices and environmental contamination, emphasizing the need for targeted interventions to mitigate PFAS exposure in high-risk regions. The implications of PFAS bioaccumulation extend beyond immediate dietary exposure, as these compounds are linked to chronic health risks such as liver damage, endocrine disruption, and cancer. Addressing PFAS risks requires a multi-pronged strategy, including improved wastewater treatment, stricter regulations on PFAS emissions, and public awareness campaigns to minimize exposure, particularly in regions with high industrial activity and reliance on fisheries.

7.2.1.1. Statistical analysis of PFAS bioaccumulation and human exposure model. The statistical analysis of PFAS bioaccumulation was conducted to evaluate the relationships between PFAS concentrations in water, bioaccumulation factors (BAF), and human PFAS intake through fish consumption across different states. This analysis incorporated three key approaches: correlation analysis to examine the strength of relationships, linear regression to quantify the effect of water concentration on human intake, and ANOVA (Miller, 1997) to identify statistically significant differences in human PFAS intake across states (as discussed in S2.2, SI). The correlation analysis (S2.2.1, Table S5 in SI) revealed strong positive relationships between PFAS water concentration, BAF, and human intake. Individual PFAS compounds, such as PFOS and PFOA, showed the strongest correlations with human intake, with coefficients of 0.94 ($p < 0.001$) and 0.92 ($p < 0.001$), respectively. Similarly, BAFs for these compounds strongly correlate with human intake, with coefficients of 0.93 ($p < 0.005$) for PFOS and 0.91 ($p < 0.005$) for PFOA. These findings suggest that states with high PFAS levels in water and elevated BAFs, such as Tamil Nadu and Gujarat, experience significantly higher human exposure through fish consumption. The linear regression analysis (S2.2.2, Table S6 in SI) quantified this relationship, demonstrating that for each 1 μg/L increase in PFAS water concentration, human PFAS intake increased by an estimated 325 μg/day for PFOS and 315 μg/day for PFOA. The regression models showed high predictive power, with R^2 values ranging from 0.86 to 0.91 ($p < 0.002$), confirming statistically significant relationships. PFOS exhibited the most potent predictive capability among the compounds, reflecting its higher bioaccumulation potential. The ANOVA results (S2.2.3, Table S7 in SI) further highlighted statistically significant differences in human PFAS intake across states. P-values for all PFAS compounds were <0.004, confirming significant variability in intake levels between states. States like Tamil Nadu and West Bengal, characterized by high PFAS concentrations in water and high fish consumption rates, had markedly higher intake levels than Rajasthan, where both PFAS concentrations and fish consumption rates are lower. These findings underscore the compounded risk posed by environmental PFAS levels and regional dietary habits, reinforcing the need for targeted PFAS management in high-risk states.

7.2.2. Long-Term exposure and risk

Long-term exposure to PFAS, even at low concentrations, poses significant health risks due to PFAS's persistence in the environment and tendency to bioaccumulate (Xu et al., 2020). Over time, PFAS exposure has been linked to chronic health issues, including cancer, liver toxicity, immune system suppression, and reproductive disorders (Xu et al., 2020). This section models the long-term exposure to PFHxS, PFOS, PFOA and PFNA in various Indian states, assessing the cumulative effects of continuous, low-level exposure on public health over decades. The risk is exceptionally high for populations that rely heavily on contaminated water sources, fish, or crops. By simulating exposure over 10, 20, and 30-year periods (2024 - 2054), we gain insight into the cumulative risks faced by different populations across India. The cumulative daily intake (CDI) metric is a widely used risk assessment tool (Bhat et al., 2023) that quantifies daily PFAS exposure per unit of body weight, offering a measure of long-term health risk. Modelling CDI over these timeframes allows us to estimate chronic health risks associated with long-term PFAS exposure in states with varying contamination levels and to identify regions where the population is most at risk.

To calculate long-term PFAS exposure, CDI is determined based on PFAS intake from drinking water, food, and air over set periods (Brown et al., 2020). The formula for the CDI is already defined in Eq. (13), Section 6.4. The CDI modelling integrates PFAS water concentrations from Table S1 in SI and bioaccumulation data from Table 5, which estimates PFAS concentrations in fish and subsequent human intake through dietary exposure. These data provide a robust foundation for assessing long-term exposure risks to individual PFAS compounds, offering insights into the cumulative health impacts of prolonged low-level exposure across selected Indian states. By combining direct intake through drinking water and indirect dietary exposure via fish consumption, Table 6 presents CDI values for individual PFAS compounds over 10, 20, and 30 years, highlighting the cumulative risks of prolonged PFAS exposure. The ingestion rate of 2 L/day aligns with adult daily water consumption, as recommended by the EPA (Langenbach and Wilson, 2021). Average body weight at 70 kg, a global standard used in environmental health models (Walpole et al., 2012). Averaging time (AT) corresponds to the total days of exposure (e.g., 3650 days for 10 years), allowing CDI to be averaged over each period, accurately representing the potential for cumulative risk.

PFAS concentrations in water, as summarized in Table S1, reflect localized contamination sources. For instance, Tamil Nadu's PFOS concentration of 0.15 μg/L reflects industrial pollution near Chennai (G. V. Koulini and Nambi, 2024), while Punjab's PFOA concentration of 0.14 μg/L emphasizes the dual impact of agro-industrial activities. These state-specific concentrations, combined with bioaccumulation factors (BAFs) specific to each compound; 5000 for PFOS, 4500 for PFOA, 4000 for PFHxS, and 3500 for PFNA, enable accurate estimation of PFAS concentrations in fish tissue, as shown in Table 5. Fish consumption rates, derived from state-specific dietary patterns (Langenbach and Wilson, 2021), further contextualize human intake, with Tamil Nadu exhibiting the highest consumption at 23 kg/year and Rajasthan the lowest at 2 kg/year. Table 6 highlights the CDI values for individual PFAS compounds, emphasizing the cumulative risks posed by long-term exposure. Tamil Nadu and Punjab exhibit the highest CDI values across all PFAS compounds, primarily due to elevated PFAS water concentrations and high fish consumption rates. For example, Tamil Nadu's PFOS CDI after 30 years reaches 0.00642 μg/kg/day, reflecting the compounded risk of high-water contamination and dietary reliance on fish. Similarly, Punjab's PFOA CDI reaches 0.00564 μg/kg/day, underscoring the heightened exposure risks in agricultural communities where untreated water is widely used for drinking and irrigation.

Moderate CDI values were observed in Maharashtra and Gujarat, where PFAS concentrations in water are relatively lower but contribute to significant cumulative risks over time. For instance, Gujarat's PFHxS CDI after 30 years is 0.00366 μg/kg/day, reflecting the long-term effects of industrial runoff on public health. Although daily intake levels appear low, PFAS's long biological half-life allows for significant bioaccumulation, increasing the likelihood of adverse health outcomes over

Table 6
Cumulative daily intake (CDI) values for various Indian states over 10, 20, and 30-Year exposure periods (2024 – 2054)[a].

State	CDI PFOS (10 years)	CDI PFOS (20 years)	CDI PFOS (30 years)	CDI PFOA (10 years)	CDI PFOA (20 years)	CDI PFOA (30 years)	CDI PFHxS (10 years)	CDI PFHxS (20 years)	CDI PFHxS (30 years)	CDI PFNA (10 years)	CDI PFNA (20 years)	CDI PFNA (30 years)
Tamil Nadu	0.0021	0.0043	0.0064	0.0020	0.0040	0.0060	0.0018	0.0037	0.0055	0.0015	0.0030	0.0045
Gujarat	0.0014	0.0029	0.0043	0.0013	0.0027	0.0040	0.0012	0.0024	0.0037	0.0010	0.0020	0.0030
Maharashtra	0.0010	0.0020	0.0031	0.00096	0.0019	0.0029	0.00088	0.0018	0.0026	0.00073	0.0015	0.0022
Uttar Pradesh	0.0010	0.0020	0.0031	0.00096	0.0019	0.0029	0.00088	0.0018	0.0026	0.00073	0.0015	0.0022
West Bengal	0.00086	0.0017	0.0026	0.00081	0.0016	0.0024	0.00074	0.0015	0.0022	0.00061	0.0012	0.0018
Andhra Pradesh	0.0015	0.0031	0.0046	0.0014	0.0029	0.0044	0.0013	0.0026	0.0040	0.0011	0.0022	0.0033
Punjab	0.0020	0.0040	0.0060	0.0019	0.0038	0.0056	0.0017	0.0034	0.0052	0.0014	0.0028	0.0043
Rajasthan	0.0011	0.0023	0.0034	0.0011	0.0021	0.0032	0.00098	0.0020	0.0029	0.00081	0.0016	0.0024

[a] CDI = Cumulative daily intake, calculated using Eq. (2). The ingestion rate (IR) was taken as 2 L/day, Exposure duration (ED) corresponds to 10, 20, and 30 years, while the average body weight was chosen as 70 kgs.

decades (Subramanian and Tanabe, 2007). Maharashtra's industrial base further illustrates the direct impact of continuous industrial discharges (Burange, 1999) on groundwater quality and public health (Khandare et al., 2015). States like Uttar Pradesh and West Bengal exhibit lower CDI values but remain at risk due to heavy reliance on contaminated water resources for agriculture and domestic use (Subramanian and Tanabe, 2007). For example, West Bengal's PFNA CDI after 30 years is 0.00183 μg/kg/day, highlighting the potential for chronic health effects in rural populations. Similarly, Andhra Pradesh and Rajasthan report lower CDI values (Suthar, 2011), such as Rajasthan's PFOS CDI of 0.00342 μg/kg/day after 30 years, due to comparatively lower PFAS concentrations in water (Duggal and Dilip, 2002). However, multi-decade exposure in these states still poses risks, particularly in agricultural areas where PFAS may accumulate in groundwater and soil, impacting food safety and human health over time.

The cumulative nature of PFAS exposure underscores the urgent need for proactive interventions. High-risk states such as Tamil Nadu and Punjab require immediate action to implement advanced water treatment technologies, enforce stricter industrial discharge regulations, and promote safe agricultural practices. Moderate-risk states, including Maharashtra and Gujarat, must focus on enhancing monitoring systems and infrastructure to manage long-term contamination. Even lower-risk states like Rajasthan and Andhra Pradesh must remain vigilant, implementing preventative measures to mitigate potential risks. Moreover, the cumulative exposure to PFAS underscores a broader public health challenge in which even low daily intake rates, when compounded over years, can have severe health impacts. Increased regulatory oversight and targeted mitigation strategies, such as restricted industrial discharges and improved water treatment infrastructure (Islamuddin et al., 2016), will be critical to reducing the long-term health risks associated with PFAS contamination across India.

7.2.2.1. Statistical analysis of cumulative daily intake (CDI) for long-term PFAS exposure. This analysis focused on the CDI of individual PFAS compounds— PFHxS, PFOS, PFOA and PFNA over 10, 20, and 30 years to understand potential long-term human exposure risks in different states. Three statistical methods were applied: correlation analysis to explore the relationship between water PFAS concentrations and CDI across time periods, linear regression to quantify the impact of PFAS concentration on CDI, and ANOVA to assess whether significant differences in CDI exist between states.

The correlation analysis (S2.3.1, Table S8 in SI) demonstrated a strong positive association between PFAS water concentrations and CDI values over time for all compounds. Pearson correlation coefficients were consistently high, with values of 0.94 for PFOS, 0.93 for PFOA, 0.91 for PFHxS, and 0.89 for PFNA ($p < 0.001$), confirming the significant role of PFAS water concentrations in determining cumulative exposure risks. These findings emphasize that states like Tamil Nadu and Punjab, with higher PFAS levels in the water, experience proportionally greater long-term CDI values, highlighting their heightened exposure risks. The linear regression analysis (S2.3.2, Table S9 in SI) quantified the relationship between PFAS water concentrations and CDI. Regression coefficients (β_1) were 0.088 for PFOS, 0.085 for PFOA, 0.083 for PFHxS, and 0.081 for PFNA, signifying that a 1 μg/L increase in water PFAS concentration results in CDI increases of 0.081 – 0.088 μg/kg/day over 30 years. The R^2 values ranged from 0.88 to 0.91, indicating that water PFAS concentrations explain 88 – 91 % of the variation in CDI values. The ANOVA results (S2.3.3, Table S10 in SI) identified statistically significant differences in CDI values across states, with P-values ranging from 0.003 to 0.006 for individual PFAS compounds. Tamil Nadu and Punjab exhibited markedly higher CDI values, as reflected in the F-statistics of 14.30 for PFOS, 12.80 for PFOA, 11.90 for PFHxS, and 10.60 for PFNA. These disparities underscore the compounded risks of higher PFAS water concentrations and prolonged exposure periods in these states. Conversely, states like West Bengal and Maharashtra exhibited relatively lower CDI values, corresponding to reduced water contamination levels. The findings also highlight the cumulative nature of PFAS exposure, emphasizing that even states with lower contamination levels must remain vigilant to prevent long-term health impacts from sustained low-level exposure. While these approximations provide a baseline for modelling, they underscore the urgent need for localized data collection in India. Regional monitoring of PFAS in WWTP effluents and atmospheric deposition is critical to refine future simulations and develop effective regulatory measures. Despite these limitations, the current model offers valuable insights into the potential contributions of point and diffuse sources to PFAS contamination in the Indian environment.

8. Health impacts of PFAS, regulatory implications and policy recommendations

PFAS pose significant risks to human health due to their persistence in the environment and ability to bioaccumulate in living organisms (Lewis et al., 2022). In India, the projected concentrations of PFAS in states such as Gujarat, Tamil Nadu, and Maharashtra, which far exceed safe levels (G. Koulini et al., 2024), present a growing public health crisis. Exposure to PFAS in these regions occurs primarily through contaminated drinking water, food sources, and direct contact with PFAS-containing consumer products (SHUKLA). Long-term exposure to PFAS concentrations above regulatory safety limits can lead to serious health outcomes, which have been increasingly documented in global scientific research (J.L. Domingo and Nadal, 2019). A detailed overview of remediation strategies for PFAS-contaminated environments, including current technologies, emerging solutions, and comparative analysis, is comprehensively discussed in Section S3 in SI and

Table 7
PFAS toxicity studies in humans and aquatic models.

Study Type	Model/Species	PFAS Compounds	Exposure Details	Key Findings	Reference
In vitro (human)	HepG2 liver cells	PFOA, GenX	0.1–100 μM	Altered cell metabolism, viability, gene expression, and global methylation state	(Drage et al., 2023)
In vitro (human)	A549 lung epithelial cells	PFOS, PFOA, PFBS, PFHxS	10–100 μM	Induced pro-inflammatory responses, altered surfactant function	(Mohapatra and Basu, 2023)
In vivo (aquatic)	Zebrafish embryos	PFOS, PFHxS, PFOA	0.1–10 μM	Developmental delays, morphological deformities, altered behavior, decreased lipid levels	(Arora et al., 2023)
Field study (India)	Fish from Ganges River	PFOS, PFOA	Environmental concentrations (ng/g)	Bioaccumulation in fish tissues, potential ecological risks	(Costello and Lee, 2020)
In vivo (rodent)	Sprague-Dawley rats	PFOS	1–5 mg/kg/day	Increased liver weight, decreased serum thyroxine, reproductive and developmental toxicity	(K.R. Binu et al., 2022)

summarised in Table S11 in SI.

8.1. Human health risks

Research has linked PFAS exposure to serious health outcomes (Table 7), many of which vary in severity depending on the compound's potency, bioaccumulation potential, and biological persistence. One of the most prominent health risks associated with PFAS exposure is cancer, particularly kidney and testicular cancer (Seyyedsalehi and Boffetta, 2023), which has been strongly associated with PFOA and PFOS, both of which exhibit high relative potency and long biological half-lives (ranging from 2 to 7 years) (Tang, 2023). Long-term exposure to compounds such as PFOA and PFOS is associated with elevated cancer risks due to their persistence in human tissues (Panieri et al., 2022). In highly contaminated regions like Gujarat and Maharashtra, continuous exposure could lead to significantly higher cancer incidences over time.

Thyroid disorders are another documented risk associated with PFAS exposure. PFOS, known for its high bioaccumulation and endocrine-disrupting potential (Sharma et al., 2022), interferes with thyroid hormone regulation, which is essential for metabolism (Coperchini et al., 2021). As a result, residents of regions with high PFAS levels, such as Tamil Nadu (Hariharan et al., 2023), could experience an increase in thyroid disorders, particularly hypothyroidism, which is especially harmful to pregnant women and infants. In addition to cancer and thyroid disorders, PFAS exposure weakens the immune system (V. Ehrlich et al., 2023). PFHxS, a compound with moderate bioaccumulation and a notably long biological half-life (5 – 8 years) (Garg et al., 2020), has been linked to immune suppression and reduced vaccine responses. Studies have shown that long-term PFAS exposure suppresses immune responses, reducing the body's ability to fight infections (V. Ehrlich et al., 2023). This is particularly concerning in states like Uttar Pradesh, where residents are predicted to experience significant PFAS exposure, leading to higher risks of infectious diseases and reduced vaccine efficacy, particularly in children.

PFAS exposure also affects reproductive health and child development. PFBS and PFNA, though less bioaccumulative, have been associated with reproductive and developmental toxicity (Pelch et al., 2019), especially in sensitive populations such as pregnant women and fetuses (Anderko and Pennea, 2020). Research indicates that women exposed to high levels of PFAS during pregnancy are at greater risk of complications such as preeclampsia (Ding et al., 2020), while newborns may suffer from developmental delays and low birth weight. In states with predicted high PFAS levels, such as Maharashtra (Nannaware et al., 2024). These reproductive health issues may become more prevalent if no action is taken to mitigate exposure. Cholesterol levels and cardiovascular health are also impacted. Compounds like PFNA and PFOA have been associated with elevated cholesterol levels due to their moderate-to-high potency and persistence in human tissues. This raises long-term cardiovascular risk. Newer PFAS alternatives, such as 6:2 FTSA and sodium p-perfluorous nonenoxybenzenesulfonate (OBS), though often perceived as less harmful, also demonstrate moderate toxicity and persistence. For example, 6:2 FTSA is associated with hepatotoxicity and lipid metabolism disruption (Sheng et al., 2017), while OBS has shown evidence of oxidative stress and thyroid hormone disruption in experimental models (Chouchene et al., 2024). These findings underscore the importance of focusing on legacy PFAS and evaluating the risks associated with substitute compounds. The combined health risks from PFAS exposure, including cancer, thyroid disorders, immune suppression, reproductive issues, and cardiovascular diseases, highlight the critical need for region-specific risk assessment and targeted intervention, particularly in high-exposure areas across India.

While many of these health risks have been identified through in vivo and in vitro studies (Nguyen et al., 2024), it is important to recognize that such studies, despite being helpful in understanding the toxicological mechanisms of PFAS, have inherent limitations. Several limitations of current model organisms (Ankeny and Leonelli, 2020) constrain their direct applicability to human health risk assessment. In vivo studies primarily conducted using rodent models often differ significantly from humans regarding metabolism (Buettner et al., 2007), pharmacokinetics, and the specific biological targets of PFAS. Rodents typically exhibit faster metabolic rates and distinct detoxification pathways than humans (Zhu, 2023; Deepika et al., 2022), potentially underestimating or overestimating specific adverse effects when extrapolating findings to human populations. Similarly, in vitro studies, although valuable for mechanistic insights, lack the complexity of whole-organism interactions, including systemic metabolism, immune responses, and chronic exposure dynamics (Deepika et al., 2022). Using isolated cell lines or primary cells cannot fully replicate human physiological conditions, potentially leading to discrepancies when predicting in vivo human responses (Allston-Roberts et al., 2010).

While many toxicological mechanisms associated with PFAS, such as oxidative stress, mitochondrial dysfunction, immune suppression, and extracellular signal-regulated kinase/mitogen-activated protein kinase (ERK/MAPK) signaling pathway activation (V. Ehrlich et al., 2023), are consistently observed in vivo studies, their relevance to humans varies depending on the model organism and the pathway studied. Oxidative stress, for example, is a conserved mechanism consistently demonstrated across rodents, zebrafish (Rericha et al., 2023), and in vitro human cell models (Rericha et al., 2023). However, signaling pathways like ERK1/2 activation (Pastore et al., 2005), involved in inflammation and apoptosis, show species-specific modulation, with variable expression patterns and sensitivities observed between rodents and humans (Willmann et al., 2020). Moreover, toxicokinetic profiles differ significantly across species: Rodents tend to eliminate PFAS more efficiently than humans due to differences in renal clearance and the expression of transporter proteins, particularly organic anion transporters (OATs) (Louisse et al., 2023). For example, the biological half-life of PFOS is approximately five years in humans (Sharma et al., 2022) but only a few weeks in mice. Such interspecies variation in absorption, distribution, metabolism, and excretion (ADME) processes impacts PFAS bioavailability and toxicity outcomes. Thus, caution is warranted when translating findings from these models directly to humans (Mangrulkar et al., 2024), highlighting the necessity of complementary epidemiological data and advanced human-relevant models, such as human organoids or

Table 8
Expanded health effects of common PFAS.

PFAS Compound	Associated Health Risks	Vulnerable Population	Relative Potency	Bioaccumulation Potential	Biological Half-life	References
PFOA	Kidney and testicular cancer, elevated cholesterol	General population, industrial workers	High	High	~2 - 4 years	(India-Aldana et al., 2023)
PFNA	Elevated cholesterol, reproductive toxicity	Adults with chronic exposure	Moderate	Moderate	~2 - 3 years	(Griffin et al., 2022)
PFBS	Developmental and reproductive toxicity	Pregnant women, fetuses	Low	Low	~1 month	(India-Aldana et al., 2023)
PFHxS	Immune suppression, low vaccine response	Children, immunocompromised individuals	Moderate	Moderate	~5 - 8 years	(Das and Janardhanan, 2022)
PFOS	Thyroid disorders, liver damage	Pregnant women, infants	High	High	~5 - 7 years	(Hák et al., 2016)
6:2 FTSA	Hepatotoxicity, lipid disruption, endocrine alteration	General population, fish consumers	Moderate	Moderate	~1.5 - 2 months*	(Haukås et al., 2007)
OBS	Oxidative stress, thyroid disruption, developmental toxicity	Pregnant women, aquatic species, infants	Moderate	Moderate	~2 - 3 months *	(Clara, 2008)

* Estimated biological half-life based on available animal or in vitro studies; human data are currently limited.

humanised animal models, to predict better the actual human health risks associated with PFAS exposure. In support of these findings, detailed toxicological evidence from human cell-based models and aquatic organisms is summarized in Table 7. This includes key studies evaluating PFAS exposure effects, such as cytotoxicity, endocrine disruption, and bioaccumulation, providing a comprehensive overview of experimentally validated health and ecological risks.

8.2. Vulnerable populations at risk

In India, vulnerable populations, particularly those living near industrial zones, agricultural areas, and contaminated water bodies, face heightened exposure risks (Kasperson and Kasperson, 2012). These risks are significantly influenced by compound-specific properties such as potency, bioaccumulation potential, and biological persistence (Table 8). Communities relying on groundwater for drinking or fishing in rivers like the Ganges are especially susceptible to long-term exposure to highly persistent compounds such as PFOS and PFHxS, which have biological half-lives exceeding five years, leading to sustained accumulation in human tissues (Selvaraj et al., 2021). These communities often lack access to alternative water sources or adequate filtration systems, exposing them to contaminated water for extended periods. Furthermore, agricultural populations who rely on contaminated groundwater for irrigation or livestock watering face a dual burden: direct exposure and indirect transfer of PFAS through the food chain. PFHxS, with its long half-life and immune-disruptive effects, poses a significant threat to such populations, especially children and immunocompromised individuals (Drew et al., 2021). Industrial workers in PFAS-related sectors, such as textiles, leather, chemical manufacturing, and firefighting, are at elevated risk due to routine handling of PFAS-containing materials (Glüge et al., 2020). These exposures include dermal contact, inhalation, and ingestion, often involving high-potency and high-accumulation compounds like PFOA and PFOS, which have been directly linked to cancers and thyroid disorders (Christensen and Calkins, 2023). Inadequate workplace protections and limited awareness further exacerbate these occupational risks than the general population.

While marketed as safer alternatives, emerging PFAS compounds like 6:2 FTSA and OBS also raise concerns. 6:2 FTSA has shown moderate bioaccumulation and endocrine-disrupting potential (Sheng et al., 2017), while OBS has been associated with oxidative stress and thyroid disruption in developing organisms (Chouchene et al., 2024). These risks may disproportionately affect pregnant women, infants, and aquatic species in nearby ecosystems where such compounds accumulate (Kamilya et al., 2022). Farmers and rural populations who consume locally produced crops and livestock raised in contaminated environments are also vulnerable. PFBS, although lower in bioaccumulation potential, can still pose developmental and reproductive toxicity risks to pregnant women and fetuses, especially in areas with repeated exposure to contaminated soil and water (G. Jha et al., 2021). Crops grown with PFAS-contaminated water can absorb these chemicals, which are then passed along the food chain to consumers (Awad et al., 2024). This complex web of exposure pathways; drinking water, occupational contact, agricultural runoff, and food chain transfer necessitates a tailored public health response. Populations in states such as Tamil Nadu, Punjab, Maharashtra, and Gujarat, where industrial activity and PFAS concentrations are high, require immediate risk mitigation strategies, including improved drinking water infrastructure, occupational safety standards, and agricultural policy interventions.

8.3. Regulatory implications and policy recommendations

The growing threat of PFAS contamination in India, exacerbated by rapid industrialization and inadequate wastewater treatment, calls for stringent regulatory actions. The long-term persistence of PFAS in the environment poses severe risks to human health and ecological systems (Hamid et al., 2023), and regulatory frameworks must be updated to meet these challenges. While India has begun recognizing the issue of chemical pollution, including PFAS, there is still a considerable gap in specific policies (Das and Janardhanan, 2022), monitoring programs and remediation strategies focused on these compounds. Globally, agencies like the US Environmental Protection Agency (EPA) and the European Union (EU) have taken proactive steps toward regulating PFAS (Brennan et al., 2021; McCleaf et al., 2023), setting a benchmark for India to follow.

In the US, the EPA has established a health advisory limit for PFOA and PFOS in drinking water (Dean et al., 2020). This guideline is based on extensive research linking PFAS exposure to adverse health effects, including immune system suppression, developmental issues, and increased cancer risk. Furthermore, the US EPA has proposed adding PFAS to the list of hazardous substances under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (Plant and Reactor, 1980), also known as Superfund. Similarly, the European Union has implemented stringent policies through its Water Framework Directive and REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) regulations (van Dijk et al., 2021), which limit the release of PFAS into the environment and mandate comprehensive monitoring programs. REACH regulations also restrict the manufacture, sale, and use of PFOS and PFOA, emphasizing the importance of protecting water resources and human health. Additionally, the EU has proposed new limits on PFAS in drinking water under its Drinking Water Directive (Tsaridou and Karabelas, 2021), which sets maximum contaminant levels for several types of PFAS, ensuring that water supplies meet strict safety standards.

India's regulatory approach to PFAS remains fragmented. The Central Pollution Control Board (CPCB), under the Ministry of Environment, Forest, and Climate Change, oversees chemical pollution in India but lacks specific regulations addressing PFAS (Puri et al., 2023). To align with global standards, India must implement policies that set enforceable limits on PFAS in industrial discharges, drinking water, and agricultural runoff. Regulatory agencies should establish mandatory monitoring programs for industries known to use PFAS, such as textiles, chemicals, and tanneries, to track contamination levels across water bodies and soils.

8.4. Policy recommendation for PFAS management in india

To effectively manage PFAS contamination in India, it is imperative to adopt a comprehensive policy framework that addresses the sources of contamination, enforces regulatory limits, and promotes sustainable remediation practices. Drawing from the regulatory approaches of the US and EU (Ronchi et al., 2019), India can strengthen its environmental policies to prevent further degradation of water and soil resources. One of the primary recommendations is the establishment of enforceable discharge limits for PFAS in industrial sources, landfills, fire training sites, and other hot spot sources. Industries such as textiles, galvanic industry, paper and pulp manufacturing, petrochemical refining, aerospace, firefighting foam (AFFF) applications, and electronics manufacturing are known to be significant sources of PFAS pollution (Cordner et al., 2021), should be required to install treatment systems that remove PFAS before releasing wastewater into the environment. These limits should be based on scientific risk assessments and aligned with international standards, ensuring they are stringent enough to protect public health and the environment. In addition to discharge limits, mandatory monitoring and reporting requirements should be enforced for industries and primary PFAS sources that use, produce or dispose of PFAS products. Industries should be required to submit regular reports on their PFAS usage and emissions, allowing regulatory agencies to track compliance and take corrective actions where necessary. In addition, the effectiveness of regulations is undermined by replacing PFAS with new PFAS with similar physicochemical properties, and thus, the essential use concept of banning PFAS where non-PFAS replacement compounds exist should be applied (Glüge et al., 2021).

Another critical policy recommendation is implementing a national PFAS monitoring program, like those established by the US EPA and the EU (Purohit and Systematic, 2023). Such a program would involve routine sampling of drinking water supplies, agricultural runoff, groundwater municipal and industrial wastewater and biosolids, and wildlife and humans across the country to assess PFAS contamination levels. The data collected through this program would provide valuable insights into the effectiveness of regulatory measures and identify areas where additional intervention is needed. India should also invest in the research and development of innovative PFAS remediation technologies.

Addressing PFAS contamination in India requires a collective effort involving academic institutions, international organizations, private-sector companies, and policymakers. Collaborative partnerships can help develop cost-effective, scalable solutions tailored to India's unique environmental and industrial landscape. These efforts would mitigate existing contamination challenges and enhance India's standing as a global leader in sustainable environmental management. Raising public awareness is another essential step in tackling PFAS contamination. Through joint initiatives involving environmental organizations, industry groups, and government agencies, educational campaigns can help inform the public about the risks of PFAS exposure and the benefits of reducing their use in consumer products. Such campaigns could promote sustainable consumption patterns and encourage the adoption of safer alternatives within industries reliant on PFAS compounds.

Furthermore, integrating PFAS management into broader environmental and public health strategies is vital. The United Nations Sustainable Development Goals (SDGs) provide a robust framework for addressing environmental challenges. Efforts to reduce PFAS pollution align directly with SDG 6, which focuses on clean water and sanitation, and SDG 12, which emphasizes sustainable consumption and production. By incorporating PFAS regulations into its strategy for achieving the SDGs, India can adopt a coordinated approach that prioritizes environmental protection and public health.

9. Conclusion

This review comprehensively assesses PFAS contamination across eight key Indian states, focusing on environmental distribution, bioaccumulation, human exposure, and regulatory challenges. The findings demonstrate the presence of PFAS compounds, including PFOS, PFOA, PFNA, PFHxS, PFBS, and 6:2 FTSA, across various environmental matrices, with industrial areas such as Tamil Nadu, Gujarat, and Punjab exhibiting the highest contamination levels. The review underscores the elevated health risks in these regions, with modeling results revealing that CDI values over 30 years significantly exceed safe thresholds, especially in areas with high fish consumption or groundwater dependence. A key contribution of this study is incorporating predictive exposure modeling, which identified critical contamination hotspots and quantified PFAS exposure through water and food sources. The bioaccumulation model, supported by state-specific fish consumption data, highlighted Tamil Nadu, West Bengal, and Andhra Pradesh as high-risk zones. Long-term CDI modeling further demonstrated that even moderate contamination levels could lead to significant human exposure over time due to the persistence of PFAS.

The review also provides a comparative toxicological analysis of PFAS compounds, integrating potency, bioaccumulation potential, and biological half-life. Notably, PFOS and PFOA remain to pose the highest risks due to their chronic toxicity and long retention in human tissues. Although less studied, emerging compounds like 6:2 FTSA and OBS exhibit concerning effects, such as endocrine disruption and oxidative stress, underscoring the need for their inclusion in regulatory frameworks. Regulatory analysis revealed that India currently lacks enforceable PFAS water, food, and soil limits, creating a critical policy gap. In contrast, countries such as the U.S. and the EU have implemented stringent limits, emphasizing the urgency for India to develop nationwide standards and adopt precautionary monitoring practices. Promising treatment methods, such as granular activated carbon (GAC) filtration, ion exchange resins, and bioremediation, offer cost-effective and scalable solutions tailored to India's environmental conditions. Public awareness campaigns are also crucial in educating communities about PFAS risks and promoting safer alternatives. Effectively addressing PFAS contamination in India will require a coordinated, multi-stakeholder approach involving regulatory agencies, researchers, industry, and civil society to implement comprehensive mitigation strategies.

Future research should prioritize expanding region-specific monitoring to establish a more comprehensive PFAS contamination profile across India, especially in under-sampled states and matrices such as soil, sediment, and biota. Toxicological studies on emerging compounds like 6:2 FTSA, OBS, and GenX should employ human-relevant models, including organoids and epidemiological cohorts, to enhance risk assessment quality. Additionally, there is an urgent need to develop and validate low-cost, scalable remediation technologies—such as biochar, electrochemical degradation, and phytoremediation—suitable for Indian environmental conditions. Integrating real-time surveillance with predictive modeling tools (e.g., AI-based risk mapping) could improve early intervention strategies. Finally, long-term health studies in vulnerable populations are essential to establish causal relationships and inform regulatory standards. Addressing these research gaps will support evidence-based policy and effective PFAS management in India.

Funding declaration

The authors declared that no funding was received for this study.

CRediT authorship contribution statement

Rajneesh Kumar Gautam: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Javad Mottaghipisheh:** Writing – review & editing, Visualization. **Saumya Verma:** Writing – review & editing, Validation, Formal analysis, Data curation. **Rajeev Pratap Singh:** Writing – review & editing, Supervision. **Shobha Muthukumaran:** Writing – review & editing, Supervision. **Dimuth Navaratna:** Writing – review & editing, Supervision. **Lutz Ahrens:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.hazadv.2025.100748.

Data availability

Data will be made available on request.

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