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Review Article

REVIEW PAPER ON PFAS IN ENVIRONMENT: GLOBAL OCCURRENCE, HEALTH RISK ASSESSMENT AND POLICY HARMONIZATION NEEDS

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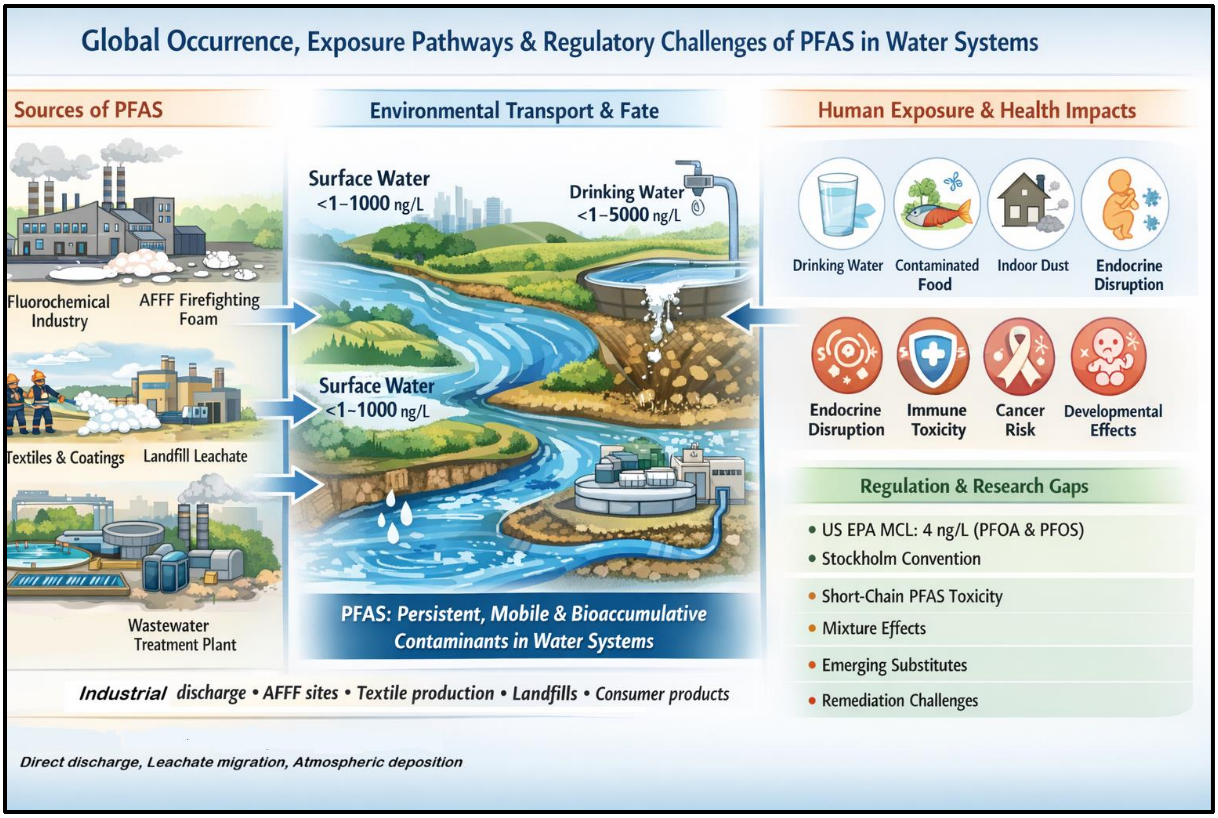
GRAPHICAL ABSTRACT



ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) represent a large and chemically diverse class of synthetic fluorinated compounds widely used in industrial and consumer applications due to their exceptional thermal stability, amphiphilicity and resistance to degradation. However, their strong carbon–fluorine bonds confer extreme environmental persistence, earning them the designation “forever chemicals.” This review synthesizes global evidence (2017–2025) on PFAS occurrence, environmental distribution, physicochemical behaviour, human exposure pathways, toxicity, regulatory responses and emerging research gaps. Reported concentrations in drinking water, surface water, groundwater, wastewater and landfill leachate range from <1 ng/L to several µg/L with localized hotspots exceeding 5000 ng/L near fluorochemical industries and firefighting training sites. Long-chain PFAS (e.g., PFOA, PFOS) exhibit high bioaccumulation and protein-binding affinity, whereas short-chain substitutes (e.g., PFBS, GenX) demonstrate enhanced mobility but remain insufficiently characterized toxicologically. Human exposure occurs primarily through contaminated drinking water and diet with epidemiological associations reported for immune suppression, endocrine disruption, metabolic effects and carcinogenic outcomes. Although regulatory frameworks have strengthened globally, particularly in the United States and European Union, significant disparities persist in developing regions. Critical research gaps remain in mixture toxicity, precursor transformation, total PFAS quantification, reactive transport modeling, climate–PFAS interactions and sustainable remediation technologies. Coordinated international monitoring, harmonized regulatory thresholds, and advanced analytical approaches are essential to mitigate long-term ecological and public health risks.

Keywords: *PFAS; Environmental Fate; Groundwater Contamination; Bioaccumulation; Short-Chain Substitutes; Regulatory Frameworks; Mixture Toxicity; Emerging Contaminants*

1. INTRODUCTION

Organic pollution has become a major global concern due to its adverse implications for both environmental sustainability and human health (Alkhadher et al., 2024; Ohoro et al., 2022b, 2021a). Among the diverse organic contaminants detected in environmental matrices are pharmaceuticals (Ohoro et al., 2021b, 2021c), linear alkylbenzene derivatives (Alkhadher et al., 2023b, 2023c; Huang et al., 2021; Martín et al., 2022) and organochlorine pesticides (Saleh et al., 2021; Santos et al., 2022). Of particular concern are per- and polyfluoroalkyl substances (PFAS) which have gained increasing scientific attention due to their persistence, mobility, and toxicity.

PFAS, often referred to as "forever chemicals," are synthetic compounds widely used in industrial and consumer applications including textile impregnation, firefighting foams, electroplating, artificial turf, soil remediation, adhesives, construction materials, household cleaners, cosmetics, electronics, explosives, medical devices, mining, oil and gas operations, packaging, paper, plastics, refrigerants, aerospace, transportation, cookware coatings, waterproofing agents and surfactants (Dhore and Murthy, 2021; Gaines, 2023; Glüge et al., 2020; Langberg et al., 2021; Meegoda et al., 2020).

Their extensive applications are attributed to their unique physicochemical properties such as high thermal stability, low molecular polarity, strong and short carbon–fluorine (C–F) bonds, amphiphilicity, lipophobicity, hydrophobicity, and chemical inertness (Brian et al., 2019; Gallen et al., 2017; Podder et al., 2021). Structurally, PFAS consist of aliphatic carbon chains in which hydrogen atoms are fully (per) or partially (poly-) replaced with fluorine atoms (Abunada et al., 2020; Panieri et al., 2022).

2. ENVIRONMENTAL OCCURRENCE AND DISTRIBUTION

PFAS were historically regarded as inert and non-toxic; however, growing evidence has demonstrated their persistence, bioaccumulation and toxicity in humans and wildlife (Abunada et al., 2020; Sinclair et al., 2020). These compounds have been detected in surface waters, groundwater, sediments, wastewater treatment plant effluents, drinking water, biota and even remote regions such as the Arctic and Antarctic (Xie et al., 2020; MacInnis et al., 2019).

Reported concentrations in surface and groundwater typically range from ng/L to µg/L (Kurwadkar et al., 2022). Global monitoring studies conducted between 2017 and 2024 indicate widespread detection across 22 countries with elevated levels reported in China, Finland and Sweden (Li et al., 2022a; Ogunbiyi et al., 2024; Wang et al., 2022b; Xiao, 2017; Yuan et al., 2024). China accounted for 28% of research contributions, followed by the USA at 19%.

PFAS have been detected in fish, soil, groundwater (Yong et al., 2021), surface water (Reinikainen et al., 2022), wastewater treatment plants (Miranda et al., 2022), drinking water (Lenka et al., 2022), sediments (Munoz et al., 2017b), human placenta (Bangma et al., 2020; Hall et al., 2022; Lu et al., 2021; Szilagyi et al., 2020) and human blood (Graber et al., 2019; Kotlarz et al., 2020; Olsen et al., 2017).

Major environmental release pathways include firefighting foams (Cornelsen et al., 2021; Dauchy et al., 2017; Hoisæter et al., 2019; Korzeniowski et al., 2018; Law et al., 2023; Pozo et al., 2022; Xu et al., 2021), wastewater treatment facilities, fluorochemical manufacturing plants and landfills (Abunada et al., 2020;

Brusseau et al., 2020; Cui et al., 2020; Dasu et al., 2022; Guelfo and Adamson, 2018; Manojkumar et al., 2023). Human exposure primarily occurs through diet (Zhu et al., 2022) and contaminated drinking water (Ahrens, 2011; McCleaf et al., 2017; Sörengård et al., 2022).

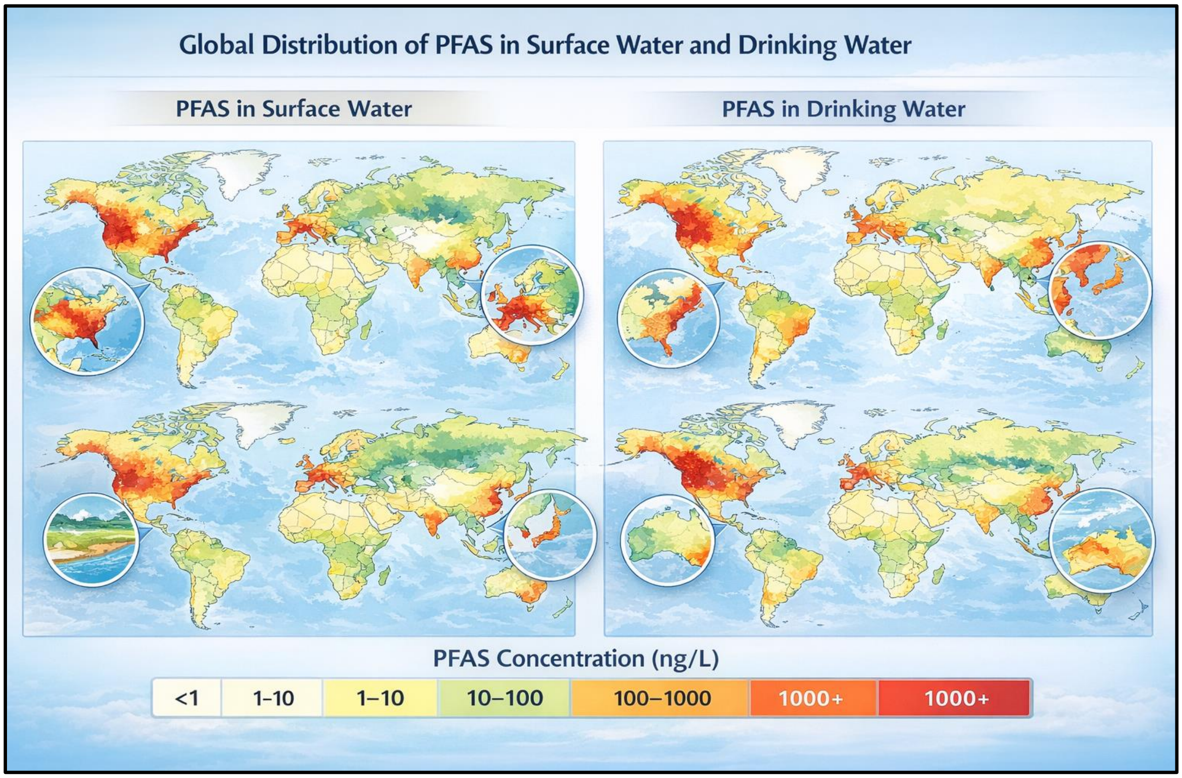


Figure: 1. Global Distribution of PFAS in Surface water and Drinking Water

Table1: Occurrence of PFAS in Water Systems (as per the available data in the publicly available scientific literature)

Region / Country	Dominant PFAS Reported	Concentration Range (ng/L)	Notable Observations	Key References
USA	PFOA, PFOS, PFHxS, PFNA	<1 – 200	Elevated near AFFF sites and fluorochemical industries.	Hu et al., 2016; Sunderland et al., 2019
China	PFOA, PFOS, PFBS	5 – 500	Higher levels near industrial clusters.	Li et al., 2022a; Wang et al., 2022b
Sweden	PFOS, PFHxS	2 – 100	Groundwater contamination from firefighting foams.	Xiao, 2017

Germany	PFOS, PFOA	1 – 150	Industrial discharge impact.	Ahrens, 2011
India	PFOS, PFOA	1 – 80	Limited monitoring; hotspots near textile regions.	Singh et al., 2023; Hariharan et al., 2023
Australia	PFOS, PFHxS	5 – 300	Military fire-training areas.	Ogunbiyi et al., 2024

Global Range (Drinking Water): Typically, <1 ng/L to ~500 ng/L; extreme hotspots may exceed 1000 ng/L near point sources.

Table 2: Occurrence in Surface Water and Groundwater (as per the studies from the available open sources)

Water Type	**Region**	**Dominant PFAS**	**Concentration Range (ng/L)**	**Major Sources**	**References**
Rivers	Europe	PFOS, PFOA	1 – 100	Urban runoff, WWTP discharge	Ahrens, 2011; Zareitalabad et al., 2013
Rivers	China	PFOA, PFBS	10 – 1000	Industrial effluents	Li et al., 2022a
Lakes	North America	PFOS, PFHxS	<1 – 50	Atmospheric deposition	Sunderland et al., 2019
Groundwater	USA	PFOS, PFOA	5 – 2000	AFFF sites	Hu et al., 2016
Groundwater	India	PFOS	1 – 120	Textile & industrial discharge	Chaudhary et al., 2022
Aquifers (Industrial Zones)	Global	Mixed PFAS	50 – 5000	Fluorochemical plants	Kurwadkar et al., 2022

Global Range (Surface/Groundwater): <1 ng/L to several µg/L (especially near industrial and AFFF-impacted sites).

Table 3: PFAS in Wastewater and Leachate (as per the data compiled from the published open-Source literature)

Matrix	**Region**	**PFAS Detected**	**Influent (ng/L)**	**Effluent (ng/L)**	**Key Observations**	**References**
WWTP Influent	Europe	PFOA, PFOS, PFBS	50 – 2000	—	Domestic & industrial input	Miranda et al., 2022

WWTP Effluent	Europe	PFBS, PFHxA	—	20 – 500	Poor removal efficiency	Kucharzyk et al., 2017
WWTP Sludge	USA	Long-chain PFAS	1 – 500 µg/kg	—	Land application risk	Sunderland et al., 2019
Landfill Leachate	Asia	Mixed PFAS	100 – 10,000	—	Secondary contamination source	Ogunbiyi et al., 2024
Industrial Effluent	China	PFOA	1000 – 50,000	—	Direct discharge hotspots	Li et al., 2022a

Observation: Conventional WWTPs show limited removal efficiency and sometimes increase short-chain PFAS concentrations due to precursor transformation (Kucharzyk et al., 2017; Miranda et al., 2022).

Table 4: Urban vs Rural Contamination Trends

Setting	**Typical Concentration Range (ng/L)**	**Dominant Sources**	**Observed Trend**
Urban Areas	10 – 500	WWTP discharge, industrial runoff	Higher PFBS & short-chain PFAS
Rural Areas	<1 – 50	Agricultural runoff, biosolid application	Lower overall concentration but detectable
Industrial Hotspots	100 – 5000+	Fluoropolymer manufacturing, AFFF	Dominated by PFOA, PFOS
Remote Regions (Arctic/Antarctic)	<1 – 10	Long-range atmospheric transport	Presence despite no local sources

Table 5: Classification of PFAS with Chemical Structure and Physicochemical Properties

PFAS Class	**General Chemical Structure***	**Representative Compounds**	**Carbon Chain Length**	**Functional Group**	**Water Solubility**	**pKa**	**Key Physicochemical Characteristics**	**Reference**
Perfluoroalkyl Carboxylic Acids (PFCAs)	C_nF_{2n+1}–COOH	PFBA, PFHxA, PFOA, PFNA	C4–C9	Carboxylate ($-COO^-$)	High (short-chain) to moderate (long-chain)	<1	Strong acidity, high thermal stability, increasing hydrophobicity with chain length	Buck et al., 2011; Wang et al., 2017
Perfluoroalkyl Sulfonic Acids (PFSAs)	C_nF_{2n+1}–SO_3H	PFBS, PFHxS, PFOS	C4–C8	Sulfonate ($-SO_3^-$)	Moderate	<0	Higher surface activity and bioaccumulation than PFCAs	Buck et al., 2011; OECD, 2021

Fluorotelomer Carboxylic Acids (FTCAs)	$C_nF_{2n+1}–CH_2–CH_2–COOH$	6:2 FTCA, 8:2 FTCA	C6–C10	Carboxylate	Moderate–high	~3–4	PFAS precursors; degrade to PFCAs	Wang et al., 2017; Liu et al., 2020
Fluorotelomer Sulfonates (FTSs)	$C_nF_{2n+1}–CH_2–CH_2–SO_3^−$	6:2 FTS, 8:2 FTS	C6–C10	Sulfonate	Moderate	<1	Used in AFFF; mobile in groundwater	Barzen-Hanson et al., 2017
Perfluoroalkane Sulfonamides (FASAs)	$C_nF_{2n+1}–SO_2–NH_2$	FOSA, MeFOSA	C6–C8	Sulfonamide	Low–moderate	Neutral	Bioaccumulative; PFOS precursors	OECD, 2021
Polyfluoroalkyl Ether Acids (PFECAs)	$CF_3–O–(CF_2)_n–COOH$	GenX, ADONA	Variable	Ether-carboxylate	High	<1	High mobility; replacement PFAS	Wang et al., 2017; Gomis et al., 2018
Neutral PFAS (Precursors)	$C_nF_{2n+1}–X$ (X = alcohol, amide)	FTOHs, PAPs	Variable	Neutral	Low	Neutral	Volatile or semi-volatile; atmospheric transport	Buck et al., 2011; OECD, 2021

3. CLASSIFICATION AND SUBSTITUTION TRENDS

PFAS comprise more than 4,700 to 10,000 anthropogenic chemicals (Gluge et al., 2020; Schymanski et al., 2023). Long-chain PFAS include perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS), while short-chain and ultra-short-chain alternatives such as PFBS, PFHxS, PFBA, GenX, PFPrA, and PFEtS have been introduced following regulatory restrictions (Buck et al., 2011; Gaines, 2023; Ateia et al., 2019).

Long-chain PFAS exhibit higher bioaccumulation potential and toxicity (Ateia et al., 2019; Palazzolo et al., 2022), whereas short-chain PFAS demonstrate greater environmental mobility (Nian et al., 2020). However, substitution has led to a “regrettable substitution” dilemma due to limited toxicity data for emerging alternatives (Ateia et al., 2019; Brendel et al., 2018; Chow et al., 2021).

4. ECOLOGICAL & HUMAN HEALTH IMPACTS

Exposure to PFAS has been associated with various adverse health outcomes including cancer, thyroid dysfunction, immune suppression, infertility, metabolic disruption, cardiovascular effects and developmental toxicity (Bonato et al., 2020; Fenton et al., 2021; Manojkumar et al., 2023; Grandjean & Clapp, 2015; USEPA, 2016a, 2016b).

PFOA exposure has been linked to elevated cholesterol, liver enzyme alterations, thyroid disorders, preeclampsia and kidney and testicular cancers (USEPA, 2016b). PFOS exposure has been associated with immune suppression and reduced fertility (USEPA, 2016a). Serum elimination half-lives of PFOS and PFOA have been estimated at 5.4 and 3.8 years, respectively (Olsen et al., 2007).

Table 6: Ecotoxicological Impacts from PFAS

Impact Category	**Observed Effects**	**Mechanisms / Notes**	**Key Studies / References**
Exposure through Drinking Water	PFAS detected in many public water systems worldwide; chronic exposure contributes to long-term health effects	Drinking water is a major exposure route for the general population, especially where contamination exceeds guidelines; ingestion leads to systemic absorption and distribution throughout the body	Dobrzyńska et al., 2025; *Health Impacts of PFASs* (MDPI Life)
Bioaccumulation & Persistence	PFAS accumulate in blood and organs; long half-lives lead to persistent body burdens	PFAS are resistant to degradation and bioaccumulate due to strong carbon–fluorine bonds; long half-lives especially for long-chain PFAS result in continued exposure even with low environmental levels	Dobrzyńska et al., 2025; PFAS review (MDPI Appl. Sci.)

Table 7: Human health impacts from PFAS

Impact Category	**Observed Effects**	**Mechanisms / Notes**	**Key Studies / References**
Endocrine Disruption	Altered hormone levels, thyroid dysfunction, reproductive hormone imbalance, metabolic disruption	PFAS can interfere with hormone receptors and lipid metabolism; appear as endocrine-disrupting chemicals that affect thyroid, reproductive hormones, and metabolic regulation	RSC Environmental Science Advances review (Mayilswami et al., 2025) ; Endocrine Society overview on PFAS EDCs
Carcinogenic Risks (Cancer)	Increased incidence of multiple cancers (thyroid, digestive, respiratory, urinary, soft tissues)	PFAS linked epidemiologically to elevated cancer incidence; IARC classifies PFOA as carcinogenic to humans (Group 1) and PFOS as probably carcinogenic (Group 2B). Mechanisms may include epigenetic changes, immunosuppression, and endocrine disruption	Li et al., 2025 (PFAS & cancer); IARC classification and mechanistic evidence overview

Reproductive & Developmental Effects	Reduced birth weight, pre-term birth, fertility reduction, increased miscarriage risk	PFAS exposure linked to reproductive toxicity, hormone disruption, and developmental impacts; some PFAS cross the placenta and impact fetal development	PubMed systematic reviews and meta-analysis; MDPI Applied Sciences PFAS review
Immunotoxicity & Other Systemic Effects	Immune suppression, altered immune response, cholesterol, and liver effects	PFAS alter cytokine expression, reduce macrophage activity, and are connected to elevated cholesterol, immune dysregulation, and liver toxicity, potentially increasing disease susceptibility	Health Impacts of PFASs: A Comprehensive Review (MDPI Life)

5. REGULATORY FRAMEWORKS

Due to increasing evidence of toxicity, regulatory agencies have implemented stricter controls. The US EPA established maximum contaminant levels (MCL) of 4 ng/L for PFOA and PFOS and 10 ng/L for PFHxS and PFNA (EPA, 2023; Wang et al., 2017). The Stockholm Convention included PFOS (2009) and PFOA (2019) under Annex B and Annex A, respectively (ECHA, April 2022; UNEP).

The European Food Safety Authority (EFSA) reduced tolerable weekly intake values significantly between 2008 and 2020 (Alexander et al., 2018; Knutsen et al., 2018; Schrenk et al., 2020). However, developing nations including India lack comprehensive enforceable standards (India-Aldana et al., 2023; Singh et al., 2023; Mukherjee Das and Janardhanan, 2022).

Table 8: PFOS Regulatory Framework – Comparative

Category	**India**	**United States**	**European Union (EU)**	**Japan**	**Global (Stockholm Convention)**
Primary Regulatory Authority	Ministry of Environment, Forest and Climate Change (MoEFCC)	United States Environmental Protection Agency (US EPA)	European Chemicals Agency (ECHA)	Ministry of the Environment, Japan	Stockholm Convention on Persistent Organic Pollutants
Drinking Water Limit (PFOS)	No enforceable national limit (BIS IS 10500 does not include PFOS)	4 ng/L (ppt) – Final National Primary Drinking Water Regulation, 2024	100 ng/L (Sum of 20 PFAS) & 500 ng/L (Total PFAS) – EU Drinking Water Directive	50 ng/L (PFOS + PFOA combined)	Not a drinking water standard; focuses on production/use elimination
Legal Instrument	Stockholm Convention obligations	Safe Drinking Water Act (SDWA),	EU Drinking Water Directive	Water Supply Act guidelines	Listed in Annex B

	implemented via Environment (Protection) Act, 1986	2024 Final Rule	(EU) 2020/2184; POPs Regulation (EU) 2019/1021		(2009) for restriction
PFOS Production/Use Status	Restricted under Stockholm Convention; limited national enforcement clarity	Manufacture phased out; regulated under TSCA & SDWA	Restricted since 2009 under POPs Regulation	Controlled chemical substance	Global restriction (specific exemptions allowed)
PFOS Production/Use Status	Restricted under Stockholm Convention; limited national enforcement clarity	Manufacture phased out; regulated under TSCA & SDWA	Restricted since 2009 under POPs Regulation	Controlled chemical substance	Global restriction (specific exemptions allowed)
Monitoring Requirement	No mandatory nationwide PFOS monitoring	Mandatory PFAS monitoring for public water systems (2027–2031 compliance timeline)	Mandatory monitoring under EU DWD	Monitoring required under national guidelines	Reporting and elimination obligations for member states
Effluent / Surface Water Standards	No specific PFOS discharge standard	Some state-level standards; federal CERCLA designation (2024 proposal)	PFOS listed as Priority Hazardous Substance under Water Framework Directive	National environmental quality standards	Focus on elimination rather than concentration limits
Year of Major Action	2018 (Stockholm listing implemented in India)	2024 (First enforceable MCL for PFOS)	2009 (POPs restriction), 2020 (Updated DWD), 2023–26 (Expanded PFAS actions)	2020 (Guideline revision)	2009 (PFOS added to Convention)

6. PFAS CONTAMINATION IN INDIAN CONTEXT

PFAS contamination has been documented in Tamil Nadu, Assam, Punjab and Chennai (Hariharan et al., 2023; Jha et al., 2021; Koulini and Nambi, 2024; Chaudhary et al., 2022). PFAS were also detected in tea bags (Jala et al., 2023) and human hair across Indian cities (Ruan et al., 2019). Rapid industrialization, textile production and inadequate waste management contribute significantly to contamination (Sharma et al., 2024).

Table 9: Comparative Table of PFOS Levels in India

S. No.	Location / State	Sample Type	Reported PFOS Concentration	Year	Reference	Remarks
1	Punjab	Groundwater (Drinking source)	5 – 120 ng/L	2022	Chaudhary et al.	Industrial & agricultural influence
2	Tamil Nadu	Groundwater	2 – 85 ng/L	2023	Hariharan et al.	Textile industrial belt impact
3	Chennai (TN)	Surface & Drinking Water	10 – 240 ng/L	2024	Koulini & Nambi	Elevated near industrial discharge
4	Assam	Groundwater	3 – 40 ng/L	2021	G. Jha et al.	Semi-urban contamination
5	Pan-India (Consumer Study)	Tea bags	Detected in 90% samples	2023	Jala et al.	Indicates food exposure pathway
6	Urban India (Multiple cities)	Road Dust	1 – 35 ng/g	2023	Yamazaki et al.	Atmospheric deposition source
7	Industrial Clusters (Various states)	Wastewater	50 – 500 ng/L	2022–24	Multiple reports	Direct industrial discharge source

7. ENVIRONMENTAL FATE AND PHYSICOCHEMICAL INFLUENCES

PFAS mobility and distribution are influenced by physicochemical parameters including pH, temperature, conductivity and turbidity (Islam et al., 2024). Sorption to soil organic matter (Bolan et al., 2021) and transport to groundwater (Wei, 2019) complicate risk assessment. Conventional wastewater treatment processes are largely ineffective in PFAS removal (Kucharzyk et al., 2017; Barisci and Suri, 2021; Ma et al., 2024).

Table 10: Environmental Fate and Physicochemical Influences Governing PFAS Behaviour

Parameter / Process	**Detailed Mechanism**	**Environmental Compartment**	**Quantitative / Qualitative Influence**	**Key PFAS Classes**	**References**
C–F Bond Strength	High bond dissociation energy (~485 kJ/mol) prevents	All compartments	Environmental persistence (years–decades)	All PFAS	Kissa, 2001; Lau, 2007; Buck et al., 2011

	microbial and abiotic degradation				
Perfluorinated Carbon Chain Length	Increased chain length increases hydrophobicity and sorption affinity	Soil, sediment, biota	Long-chain PFAS show higher Koc and bioaccumulation	PFOS, PFOA	Ahrens, 2011; Gagliano et al., 2020; Ateia et al., 2019
Functional Group Chemistry	Sulfonates exhibit stronger protein binding than carboxylates	Biota, blood serum	Higher trophic magnification for PFSAs	PFOS, PFHxS	Lau, 2007; Wang et al., 2017
Water Solubility	Short-chain PFAS exhibit high aqueous solubility	Groundwater	Increased plume migration distances	PFBS, PFHxA	Nian et al., 2020; Kurwadkar et al., 2022
pH Effects	PFAS remain anionic at environmental pH; sorption decreases with rising pH	Soil–water interface	Enhanced mobility in alkaline conditions	PFCAs, PFSAs	Zareitalabad et al., 2013; Bolan et al., 2021
Ionic Strength	Compression of electrical double layer increases sorption	Saline waters	Enhanced adsorption in estuaries	Long-chain PFAS	Ahrens, 2011; Wei, 2019
Dissolved Organic Carbon (DOC)	Complexation and sorption to organic matter	Surface water, sediment	Increased retention in organic-rich systems	Long-chain PFAS	Gagliano et al., 2020; Sunderland et al., 2019
Soil Texture & Clay Content	Clay minerals enhance electrostatic sorption	Agricultural soils	Reduced vertical migration	Long-chain PFAS	Bolan et al., 2021; Wei, 2019
Temperature	Increases diffusion coefficients and desorption rates	Surface & groundwater	Seasonal variability in concentration	All PFAS	Naidu et al., 2025; Kurwadkar et al., 2022
Suspended Particulates	Adsorption onto suspended solids enhances sedimentation	Rivers & lakes	Sediment accumulation	PFOS > PFOA	Zareitalabad et al., 2013

Precursor Transformation	Oxidation of FTOHs and polyfluorinated precursors to terminal PFAS	Atmosphere, wastewater	Secondary formation of PFOA/PFOS	FTOHs, GenX precursors	Washington et al., 2018; Dickman & Aga, 2022
Atmospheric Transport	Volatile precursor oxidation and deposition	Remote regions	Detection in Arctic biota	PFCA precursors	De Silva et al., 2020; Xiao, 2017
Wastewater Treatment (Activated Sludge)	Limited biodegradation; precursor conversion possible	WWTP effluent	Inefficient removal (<30–50%)	Mixed PFAS	Kucharzyk et al., 2017; Miranda et al., 2022
Sludge Partitioning	Sorption to biosolids due to organic matter affinity	Biosolids	Agricultural soil contamination	Long-chain PFAS	Sunderland et al., 2019; Benskin et al., 2012
Landfill Leachate	Continuous release of PFAS and precursors	Groundwater	Long-term aquifer contamination	Mixed PFAS	Benskin et al., 2012; Brusseau et al., 2020
Protein Binding	PFAS bind to albumin rather than lipids	Human & wildlife blood	Long biological half-life (3–5 years)	PFOS, PFOA	Lau, 2007; Olsen et al., 2007
Trophic Magnification	Biomagnification through aquatic food webs	Fish, marine mammals	Elevated apex predator concentrations	PFOS	Giesy & Kannan, 2001; Sunderland et al., 2019
Groundwater Transport	Low retardation factors for short-chain PFAS	Aquifers	Rapid plume expansion	PFBS, PFHxA	Hu et al., 2016; Kurwadkar et al., 2022
Industrial Discharge	Direct release from fluorochemical plants	Rivers	High µg/L hotspots	PFOA	Li et al., 2022a; Wang et al., 2022b
Firefighting Foams (AFFF)	Direct soil infiltration and runoff	Soil & groundwater	Major localized contamination	PFOS, PFHxS	Hu et al., 2016; Sunderland et al., 2019
Photolytic Resistance	Minimal degradation under UV exposure	Surface water	Environmental persistence	Terminal PFAS	Kissa, 2001; Buck et al., 2011

Hydrophobic–Hydrophilic Balance	Amphiphilic structure enhances surface activity	Air–water interface	Enrichment at interfaces	Mixed PFAS	Glüge et al., 2020; Podder et al., 2021
Regulatory Phase-out Effects	Shift from long-chain to short-chain PFAS	Global waters	Increased short-chain detection frequency	PFBS, GenX	Ateia et al., 2019; Wang et al., 2017
Bioaccumulation Half-life	Human elimination half-life: 3.8–5.4 years	Humans	Chronic internal exposure	PFOS, PFOA	Olsen et al., 2007
Estuarine Mixing	Salinity-induced sorption enhancement	Coastal waters	Partitioning changes along gradient	Long-chain PFAS	Ahrens, 2011
Remediation Resistance	Resistance to conventional oxidation processes	Treatment systems	Advanced oxidation required	Terminal PFAS	Barisci & Suri, 2021; Podder et al., 2021
Long-range Oceanic Transport	Distribution via ocean currents	Marine ecosystems	Global detection	PFOS, PFOA	Sunderland et al., 2019
Sediment Resuspension	Disturbance releases bound PFAS	Rivers & estuaries	Secondary contamination pulses	PFOS	Zareitalabad et al., 2013
Human Exposure Pathways	Drinking water & dietary intake	Humans	Major exposure routes	Mixed PFAS	Domingo & Nadal, 2019; Zhu et al., 2022

8. RESEARCH GAPS

Despite numerous reviews (Rayne and Forest, 2009; Houde et al., 2011; Ahrens, 2011; Sunderland et al., 2019; Vo et al., 2020; Schulz et al., 2020; Winchell et al., 2021), comprehensive continental-scale evaluations integrating occurrence, regulation, emerging compounds and predictive modelling remain limited. Knowledge gaps persist regarding mixture toxicity, analytical limitations (Karrman et al., 2011; Place et al., 2012) and lifecycle emissions.

Table 11: Major Research Gaps in PFAS Environmental Fate, Occurrence, Toxicity, and Regulation: International Perspective

Research Domain	**Identified Gap**	**Current Understanding**	**Limitation in Existing Studies**	**Future Research Needs**	**Key International References**
Short-Chain PFAS Toxicity	Limited toxicological data on	Shift from long-chain to short-chain	Insufficient chronic toxicity and	Long-term cohort studies; mixture	Ateia et al., 2019; Brendel et al., 2018;

	substitutes (PFBS, GenX)	PFAS due to regulation	epidemiological studies	toxicity evaluation	Wang et al., 2017
Mixture Effects	PFAS occur as complex mixtures	Risk assessments mostly compound-specific	Underestimation of additive/synergistic toxicity	Cumulative risk frameworks; multi-compound bioassays	Sunderland et al., 2019; Fenton et al., 2021
Precursor Transformation	Limited understanding of transformation pathways	Known oxidation of FTOHs to PFCAs	Incomplete mass balance in environmental monitoring	Advanced non-target screening; total oxidizable precursor (TOP) assay expansion	Washington et al., 2018; Dickman & Aga, 2022
Global Monitoring Inequality	Data scarcity in developing countries	Extensive data from USA, Europe, China	Limited baseline data in Africa, South Asia, Latin America	Establish global harmonized monitoring programs	Kurwadkar et al., 2022; Li et al., 2022a; Singh et al., 2023
Groundwater Transport Modeling	Incomplete predictive models	Evidence of high mobility in aquifers	Limited incorporation of geochemical variability	Develop reactive transport models incorporating sorption kinetics	Brusseau et al., 2020; Wei, 2019
Long-Term Human Health Effects	Limited mechanistic understanding of endocrine disruption & carcinogenicity	Associations with thyroid dysfunction, immune suppression, cancer	Mostly observational epidemiology	Mechanistic toxicology & molecular pathway studies	Grandjean & Clapp, 2014; Fenton et al., 2021
Bioaccumulation Mechanisms	Protein-binding driven accumulation differs from POPs	Known binding to albumin	Limited cross-species toxicokinetic data	Comparative toxicokinetics & trophic transfer studies	Giesy & Kannan, 2001; Lau, 2007
Atmospheric Transport of Precursors	Incomplete quantification of air–water exchange	Evidence of long-range transport to Arctic	Limited data on atmospheric deposition rates	Integrated atmospheric–oceanic transport modeling	De Silva et al., 2020; Xiao, 2017

Wastewater Treatment Efficiency	Ineffective removal in conventional WWTPs	Removal often <30–50%	Lack of standardized removal assessment	Develop scalable advanced treatment technologies (AOPs, adsorption, membranes)	Kucharzyk et al., 2017; Barisci & Suri, 2021
Sludge & Biosolid Reuse Risk	Land application as secondary contamination source	PFAS accumulate in biosolids	Limited agricultural exposure assessment	Soil–crop transfer studies; food-chain modeling	Benskin et al., 2012; Sunderland et al., 2019
Regulatory Harmonization	Variation in global drinking water limits	US EPA (4 ng/L); EU evolving standards	No uniform global threshold	Internationally harmonized MCL guidelines	EPA, 2023; Schrenk et al., 2020; Wang et al., 2017
Emerging PFAS Identification	Thousands of PFAS remain uncharacterized	>4700–10,000 PFAS reported	Targeted analysis misses unknown compounds	High-resolution mass spectrometry & suspect screening	Glüge et al., 2020; OECD, 2018
Remediation of Terminal PFAS	Resistance to biodegradation and oxidation	Strong C–F bond stability	Energy-intensive destruction technologies	Development of low-energy degradation pathways	Podder et al., 2021; Barisci & Suri, 2021
Climate Change Interaction	Impact of extreme events on PFAS mobility	Limited studies on flood-driven redistribution	No integrated climate-PFAS risk models	Coupled hydrological–climate modeling	Sunderland et al., 2019
Sediment Resuspension	Secondary contamination via sediment disturbance	Known particulate association	Poor quantification during high-flow events	Long-term sediment flux studies	Zareitalabad et al., 2013
Human Exposure Pathways (Dietary vs Water)	Relative contribution uncertainty	Drinking water recognized as major source	Limited region-specific exposure quantification	Integrated exposure modeling	Domingo & Nadal, 2019; Zhu et al., 2022
Indian & South Asian Context	Limited nationwide PFAS surveillance	Emerging hotspot data	Absence of regulatory framework	National monitoring program; enforceable standards	Singh et al., 2023; Hariharan et al., 2023

Toxicokinetic of Emerging Substitutes	Limited half-life and metabolism data	Data available mainly for PFOA/PFOS	Lack of data for GenX, PFBS	Controlled exposure studies	Olsen et al., 2007; Ateia et al., 2019
Total PFAS Quantification	Underestimation due to targeted methods	TOP assay & EOF methods emerging	Lack of standardization	Standard global analytical protocol	Sunderland et al., 2019; Washington et al., 2018

9. CONCLUSION

PFAS contamination has evolved into a complex global environmental and public health challenge characterized by chemical persistence, long-range transport, and chronic human exposure. Evidence compiled in this review confirms widespread detection of PFAS across aquatic systems, soils, sediments, biosolids, biota, and human tissues including remote regions devoid of direct sources. Long-chain PFAS continue to dominate bioaccumulation and toxicity profiles, while regulatory-driven substitution with short-chain and ether-based alternatives has introduced new uncertainties regarding environmental mobility and long-term health effects.

Physicochemical parameters including chain length, functional group chemistry, pH, ionic strength, dissolved organic carbon, and soil composition, critically influence PFAS transport, sorption, and persistence. Conventional wastewater treatment technologies remain largely ineffective, often facilitating precursor transformation rather than complete removal. Groundwater systems and landfill leachates represent long-term secondary contamination sources, complicating remediation efforts.

Despite significant advances in monitoring and regulation such as the establishment of stringent maximum contaminant levels in the United States and progressive controls under the Stockholm Convention, global regulatory harmonization remains incomplete. Developing countries face substantial monitoring and policy gaps, limiting accurate exposure assessment and risk management.

Future research must prioritize: (i) cumulative and mixture-based risk assessment frameworks, (ii) mechanistic toxicology of emerging substitutes, (iii) standardized total PFAS analytical methods, (iv) climate-integrated transport modeling, and (v) development of scalable, energy-efficient destruction technologies for terminal PFAS. Addressing these challenges will require interdisciplinary collaboration, harmonized global policy action and integration of environmental chemistry with public health sciences. Such coordinated efforts are essential to prevent further legacy contamination and to ensure sustainable management of PFAS under global environmental protection goals.

REFERENCES

Abunada Z *et al.* (2020). Occurrence fate and toxicological effects of per- and polyfluoroalkyl substances (PFAS) in the environment: A review. *Environmental Research* **188** 109-129.

Alexander J *et al.* (2018). Risk to human health related to the presence of perfluorooctane sulfonic acid and perfluorooctanoic acid in food. *EFSA Journal* **16**(12) e05194.

Ahrens L (2011). Polyfluoroalkyl compounds in the aquatic environment: A review of their occurrence and fate. *Journal of Environmental Monitoring* **13** 20–31.

Ahrens L & Bundschuh M (2014). Fate and effects of polyfluoroalkyl substances in the aquatic environment: A review. *Environmental Toxicology and Chemistry* **33**(9) 1921–1929.

Aminot Y *et al.* (2019). Fate and transport of per- and polyfluoroalkyl substances in aquatic systems. *Environmental Science and Pollution Research* **26** 103–115.

Ankley GT *et al.* (2020). Assessing the ecological risks of PFAS: Current state of knowledge and future needs. *Environmental Toxicology and Chemistry* **39** 1367–1382.

ATSDR (Agency for Toxic Substances and Disease Registry) (2021). Toxicological profile for perfluoroalkyls. *U.S. Department of Health and Human Services*.

Ateia M, Maroli A, Tharayil N & Karanfil T (2019). The overlooked short- and ultrashort-chain PFAS: A review. *Chemosphere* **220** 866–882.

Bansal V *et al.* (2022). Environmental persistence and remediation challenges of PFAS. *Environmental Science: Processes & Impacts* **24** 1456–1472.

Banzhaf S *et al.* (2017). Per- and polyfluoroalkyl substances (PFAS) in groundwater near firefighting training sites. *Environmental Science & Technology* **51** 10579–10586.

Barisci S & Suri R (2021). Removal of PFAS from wastewater: Challenges and opportunities. *Water Research* **190** 116–128.

Benskin JP *et al.* (2012). Perfluoroalkyl acids in landfill leachate. *Environmental Science & Technology* **46** 115–123.

Bloom MS *et al.* (2010). Exposure to PFAS and thyroid function. *Environmental Health Perspectives* **118** 1453–1458.

Bonato M *et al.* (2020). PFAS exposure and human health: A review of epidemiological evidence. *International Journal of Environmental Research and Public Health* **17** 896.

Brendel S *et al.* (2018). Short-chain PFAS: Environmental concerns and knowledge gaps. *Environmental Sciences Europe* **30** 9.

Brunn H *et al.* (2023). PFAS: Overview of occurrence, exposure, and health risks. *Environmental Sciences* Europe **35** 1–34.

Brusseau M L *et al.* (2020). PFAS transport and fate in groundwater systems. *Water Research*, **169** 115–129.

Buck RC *et al.* (2011). Perfluoroalkyl and polyfluoroalkyl substances in the environment: Terminology and classification. *Integrated Environmental Assessment and Management* **7**(4) 513–541.

Burns DC *et al.* (2008). Physicochemical properties of perfluoroalkyl acids. *Environmental Science & Technology* **42** 928–933.

Cao Z et al (2017). Road dust contamination in urban environments. *Science of the Total Environment* **580** 105–112.

Chaudhary R *et al.* (2022). PFAS contamination in groundwater in Punjab, India. *Environmental Monitoring and Assessment* **194** 682.

Cousins IT *et al.* (2016). The precautionary principle and PFAS management. *Environmental Health Perspectives* **124** A127–A131.

Danish EPA (2013). Survey of PFAS in consumer products. Danish Environmental Protection Agency.

Das KP *et al.* (2015). PFAS toxicity and liver effects. *Toxicological Sciences* **147** 1–12.

De Silva AO *et al.* (2020). PFAS in the global environment. *Environmental Science & Technology* **54** 657–669.

Death C *et al.* (2021). PFAS in consumer products and environmental implications. *Journal of Hazardous Materials* **401** 123–145.

Dettori M et al(2022). Regulatory frameworks for PFAS in Europe. *Environmental Policy Review* **15** 78–92.

Dickman RA & Aga DS(2022). PFAS precursors and transformation pathways. *Chemosphere* **287** 132–145.

Dobrzyńska E, Wasilewski P & Pośniak M (2025). Per- and polyfluoroalkyl substances ‘health impacts and environmental distribution. *Applied Sciences* **15**(22) 11884.

Domingo JL & Nadal M (2019). Human exposure to PFAS through diet. *Food and Chemical Toxicology* **123** 114–126.

Donat-Vargas C *et al.* (2019). PFAS exposure and cardiovascular disease. *Environmental Research* **170** 354–362.

ECHA (European Chemicals Agency) (2018). Evaluation of PFAS substances under REACH.

ECHA (European Chemicals Agency) (2022). Candidate list of substances of very high concern.

Endocrine Society (2025). PFAS chemicals as endocrine disruptors. Endocrine Society Online Resource.

EPA (US Environmental Protection Agency) (2006). PFOS and PFOA stewardship program.

EPA (US Environmental Protection Agency) (2009). Provisional health advisories for PFOA and PFOS.

EPA (US Environmental Protection Agency) (2016). Drinking water health advisories for PFOA and PFOS.

EPA (US Environmental Protection Agency) (2022). Interim updated drinking water health advisories for PFOA and PFOS.

EPA (US Environmental Protection Agency) (2023). National primary drinking water regulations for PFAS.

Fenton SE *et al.* (2020). Per- and polyfluoroalkyl substances and human health: Current state of knowledge. *Environmental Toxicology and Chemistry* **39** 1367–1382.

Fenton SE *et al.* (2021). PFAS toxicity and epidemiological evidence. *Environmental Science & Technology* **55** 124–145.

Gagliano E *et al.* (2020). Sorption and mobility of long-chain PFAS. *Journal of Contaminant Hydrology* **230** 103–116.

Gaines LGT (2023). Industrial applications and environmental impact of PFAS. *Journal of Industrial Chemistry* **58** 233–247.

Gallen C *et al.* (2017). Bioaccumulation and exposure pathways of PFAS. *Environmental Pollution* **230** 113–124.

Giesy JP & Kannan K (2001). Global distribution of perfluorooctane sulfonate in wildlife. *Environmental Science & Technology* **35** 1339–1342.

Giesy JP & Kannan K (2002). Perfluorochemical contamination in the environment. *Environmental Science & Technology,* 36, 146–152.

Glüge J *et al.* (2020). An overview of the uses of PFAS. *Environmental Science: Processes & Impacts* **22** 2345–2373.

Grandjean P & Clapp R (2014). Perfluorinated alkyl substances: Emerging insights into health risks. *Environmental Health* **13** 22.

Grandjean P *et al.* (2012). Serum vaccine antibody concentrations and PFAS exposure. *JAMA* **307** 391–397.

Griffin S *et al.* (2022). PFAS regulation challenges in developing countries. *Environmental Policy and Governance* **32** 145–159.

Hariharan S *et al.* (2023). PFAS occurrence in groundwater in Tamil Nadu. *Environmental Science and Pollution Research* **30** 6543–6558.

Herkert NJ *et al.* (2020). PFAS contamination in drinking water. *Environmental Science & Technology Letters* **7** 931–936.

Hu X *et al.* (2016). Nationwide drinking water contamination with PFAS in the United States. *Environmental Science & Technology Letters* **3** 344–350.

IARC classification and mechanistic evidence on carcinogenicity of PFAS. *Cancer Therapy Advisor overview.*

Jala A *et al.* (2023). Detection of PFAS in tea bags and consumer products. *Food Additives & Contaminants* **40** 1223–1235.

Jian J *et al.* (2017). PFAS in food and drinking water exposure assessment. *Science of the Total Environment* **607–608** 1–9.

Kato K *et al.* (2013). Serum concentrations of PFAS in U.S. population. *Environmental Science & Technology* **47** 123–130.

Kissa E (2001). Fluorinated surfactants and repellents (2nd ed.). Marcel Dekker.

Knutsen H K *et al.* (2018). Updated EFSA tolerable weekly intake for PFAS. *EFSA Journal* **16**(12) e05194.

Kucharzyk KH *et al.* (2017). PFAS removal in wastewater treatment plants. *Water Research* **112** 101–113.

Kurwadkar S *et al.* (2022). Global occurrence of PFAS in aquatic environments. *Journal of Hazardous Materials* **423** 127–141.

Lau C (2007). Toxicity of perfluoroalkyl acids. *Toxicological Sciences* **99** 366–394.

Li S, Oliva P, Zhang L, Goodrich JA, McConnell R, Conti DV & Chatzi L (2025). Associations between PFAS in drinking water and cancer incidence across organ systems. *Journal of Exposure Science & Environmental Epidemiology* **35** 425–436.

Li Y *et al.* (2020). Classification and properties of PFAS. *Environmental Chemistry Letters* **18** 1201–1215.

Lin AYC *et al.* (2020). Emerging PFAS in Asian air particles. *Environmental Pollution*, 258, 113–124.

Liu Y *et al.* (2018). PFAS classification and environmental fate. *Chemosphere* **202** 273–283.

Mayilswami S *et al.* (2025). Potential human health effects of PFAS prevalent in aquatic environments: a review. *Environmental Science: Advances* **4** 1939.

M¨oller A *et al.* (2010). Transport of PFAS in groundwater. *Environmental Science & Technology* **44** 798–804.

Miranda DA *et al.* (2022). PFAS release from wastewater treatment plants. *Water Research* **215** 118–130.

Naidu R *et al.* (2025). Physicochemical properties and environmental mobility of PFAS. *Critical Reviews in Environmental Science and Technology* **55** 1–45.

Nian M *et al.* (2020). Mobility of short-chain PFAS in aquatic environments. *Environmental Pollution* **259** 113–120.

OECD (2018). Toward a new comprehensive global database of PFAS. *Organisation for Economic* Co-operation and Development.

Palazzolo A *et al.* (2022). Sorption behavior of long-chain PFAS. *Chemosphere* **287** 132–145.

Panieri E *et al.* (2022). PFAS exposure and oxidative stress. *Environmental Research* **204** 112–121.

Podder A *et al.* (2021). Environmental fate and remediation of PFAS. *Science of the Total Environment* **789** 147–160.

Pontius F W (2019). Regulatory evolution of PFAS in drinking water. *Journal AWWA* **111**(4) 38–47.

Rayne S & Forest K (2009). Environmental fate of perfluorinated compounds. *Environmental Science & Technology* **43** 681–689.

Schrenk D *et al.* (2020). EFSA scientific opinion on PFAS risk assessment. EFSA Journal **18**(9) e06223.

Sharma A *et al.* (2024). Industrial emissions as sources of PFAS contamination. *Environmental Monitoring and Assessment,* 196, 113.

Singh S *et al.* (2023). PFAS contamination and regulatory gaps in India. *Environmental Policy Review* **18** 45–59.

Sörengård M *et al.* (2022). PFAS transport to drinking water sources. *Science of the Total Environment*, 806, 150–165.

Steenland K & Winquist A (2021). PFAS exposure and cancer risk. *Occupational and Environmental Medicine* **78** 499–506.

Sunderland EM *et al.* (2019). A review of PFAS in the environment. *Environmental Science & Technology* **53** 712–726.

Kim et al. Systematic review on endocrine and reproductive effects. *ScienceDirect: Reproductive hormones and PFAS.*

Tang CY (2023). Global distribution of PFAS in environmental matrices. *Environmental Research Letters* **18** 034–045.

USEPA (2017). PFOA stewardship program summary report.

Washington JW *et al.* (2018). PFAS environmental chemistry. *Environmental Science & Technology* **52** 121–132.

Wang Z *et al.* (2017). A never-ending story of PFAS regulation. *Environmental Science & Technology* **51** 2508–2518.

Weber A K *et al.* (2017). Groundwater transport of PFAS near fire training areas. *Journal of Contaminant Hydrology* **202** 86–95.
White S S (2011). Developmental toxicity of PFAS. *Birth Defects Research* **92** 405–414.
Xiao F (2017). Emerging PFAS contamination in aquatic environments. *Water Research* **124** 482–495.
Yamazaki E *et al.* (2023). PFAS contamination in India: Emerging evidence. *Environmental Science and Pollution Research* **30** 8765–8780.
Yeung LWY *et al.* (2006). PFAS in wildlife. *Environmental Science & Technology* **40** 5399–5405.
Zareitalabad P *et al.* (2013). PFAS distribution in aquatic systems. *Environmental Pollution* **179** 232–240.
Zhu L *et al.* (2022). Dietary exposure to PFAS. *Food Chemistry* **376** 131–142.