

Review

PFAS Governance for Sustainable Environmental Management: Regulatory Frameworks and Future Directions

Thomas Ingwani *, James Ramontja and Caliphs Zvinowanda

Chemical Sciences Department, University of Johannesburg, Johannesburg 2028, South Africa; jamesr@uj.ac.za (J.R.); czvinowanda@uj.ac.za (C.Z.)

* Correspondence: thomasi@uj.ac.za; Tel.: +27-780899112

Abstract

Per- and polyfluoroalkyl substances (PFAS) have emerged as a major global environmental challenge because of their widespread use, exceptional persistence, environmental mobility, bioaccumulation potential, and associated risks to human and ecosystem health. Their continued release threatens water security, environmental quality, and sustainable development, highlighting the need for effective governance and sustainable chemical management. This review critically evaluates PFAS governance by synthesising recent advances in regulatory frameworks, environmental monitoring, and environmental risk management across major international jurisdictions. The analysis demonstrates that effective PFAS governance extends beyond establishing regulatory limits and depends on integrated approaches combining class-based regulation, harmonised environmental monitoring, adaptive governance, robust enforcement, and stakeholder collaboration. Despite significant regulatory progress, persistent challenges, including fragmented governance, inconsistent monitoring capacity, limited toxicological data for emerging PFAS, and disparities in institutional resources, continue to hinder effective management. The review identifies international regulatory harmonisation, expanded monitoring of emerging PFAS, advanced analytical technologies, improved data sharing, and integration of One Health and circular economy principles as priorities for strengthening future governance. Collectively, these findings provide a comprehensive framework to support evidence-based policymaking, sustainable PFAS management, and long-term protection of human health and the environment while contributing to the achievement of the United Nations Sustainable Development Goals.

Keywords: per- and polyfluoroalkyl substances (PFAS); environmental governance; environmental monitoring; environmental risk assessment; sustainable development; sustainable chemical management; circular economy; Sustainable Development Goals (SDGs); environmental sustainability; regulatory frameworks

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1. Introduction

Per- and polyfluoroalkyl substances (PFAS) are synthetic fluorinated compounds defined by strong carbon-fluorine bonds [1]. Classified into long- and short-chain types, they include perfluorooctanoic acid (PFOA) and perfluorooctane sulphonate (PFOS) [2]. The exceptional thermal stability, chemical resistance, hydrophobicity, and lipophobicity of PFAS have driven their extensive use in industrial processes and consumer products. Applications span aqueous film-forming foams (AFFFs), cookware, textiles, packaging,

cosmetics, plating, electronics, and semiconductors [3,4]. Widespread use has led to global distribution across aquatic, terrestrial, and atmospheric systems, with PFAS contamination detected in waters, soils, sediments, wildlife, and remote polar regions [5].

PFAS, commonly termed “forever chemicals,” persist because of the exceptional stability of their carbon–fluorine bonds, leading to long-term environmental persistence and toxicological concern [6,7]. Although the term has increased public awareness and regulatory attention, it may oversimplify the diversity of the PFAS class, whose compounds differ markedly in chemical structure, environmental behaviour, mobility, bioaccumulation, and toxicity. It may also create unrealistic expectations that PFAS contamination cannot be effectively managed. In practice, integrated strategies combining source reduction, class-based regulation, advanced treatment technologies, long-term environmental monitoring, and adaptive governance can substantially reduce environmental releases and human exposure. Thus, “forever chemicals” should be regarded as a communication tool rather than a precise scientific description. Major contamination pathways include wastewater effluents, industrial emissions, landfill leachate, biosolid application, and firefighting foams [8,9].

The increasing recognition of PFAS contamination as a global environmental and public health crisis has shaped environmental governance. Scientific evidence of widespread occurrence, persistence, long-range transport, and potential health effects, reinforced by media coverage, contamination incidents, litigation, and public concern, has elevated PFAS to a major policy priority [10–12]. Consequently, governments have strengthened regulatory frameworks, monitoring programmes, remediation efforts, and international cooperation while emphasising evidence-based decision-making, transparent risk communication, and adaptive governance to balance environmental, public health, and socioeconomic priorities [10,13].

PFAS exposure has been associated with endocrine disruption, immunotoxicity, developmental and reproductive effects, liver dysfunction, and increased cancer risk, with exposure occurring through drinking water, food, occupational activities, inhalation, and consumer products [14,15]. PFAS also threaten aquatic ecosystems, wildlife, and biodiversity, prompting regulatory standards, environmental monitoring, and phase-out initiatives despite persistent governance gaps [12,16]. Beyond these impacts, PFAS contamination represents a major sustainability challenge affecting natural resources, ecosystems, food chains, and public health while increasing remediation and healthcare costs. Consequently, effective PFAS governance must integrate sustainable chemical management, circular economy principles, responsible production and consumption, and evidence-based environmental policy. This review critically compares international regulatory frameworks, environmental monitoring programmes, and risk management strategies to evaluate their contributions to pollution prevention, environmental resilience, and sustainable development aligned with the United Nations Sustainable Development Goals [17].

Although numerous reviews have examined PFAS occurrence, analytical methods, toxicity, remediation, exposure pathways, and regulatory developments, few have integrated regulatory frameworks, environmental monitoring, governance effectiveness, adaptive management, sustainability principles, and recent international policy developments within a single framework. This review addresses that gap by proposing an integrated governance perspective based on class-based regulation, adaptive governance supported by continuous environmental monitoring, and stakeholder collaboration. It further demonstrates that effective implementation remains constrained by fragmented regulatory systems, inconsistent monitoring capacity, limited toxicological data for emerging PFAS, and disparities in institutional resources. By synthesising scientific evidence with regulatory practice, this review provides practical guidance for

policymakers, researchers, industry, and regulators while identifying priorities for future research and international cooperation.

2. Review Methodology and Manuscript Preparation

2.1. Literature Search Strategy

This review employed a structured literature review approach informed by the PRISMA 2020 framework to enhance transparency, reproducibility, and methodological rigour [18]. It critically evaluated PFAS governance, regulatory frameworks, environmental monitoring, risk assessment, remediation, and sustainable environmental management. A comprehensive literature search was conducted using Scopus, Web of Science, PubMed, and Google Scholar, supplemented by international regulatory documents, policy reports, reference lists of key reviews, and selected grey literature published by recognised governmental and international organisations.

The search strategy combined keywords and Boolean operators, including “PFAS”, “PFAS governance”, “PFAS regulation”, “environmental monitoring”, “environmental risk assessment”, “drinking water”, “regulatory framework”, “environmental policy”, “remediation”, “sustainability”, and related search terms to maximise retrieval of relevant publications.

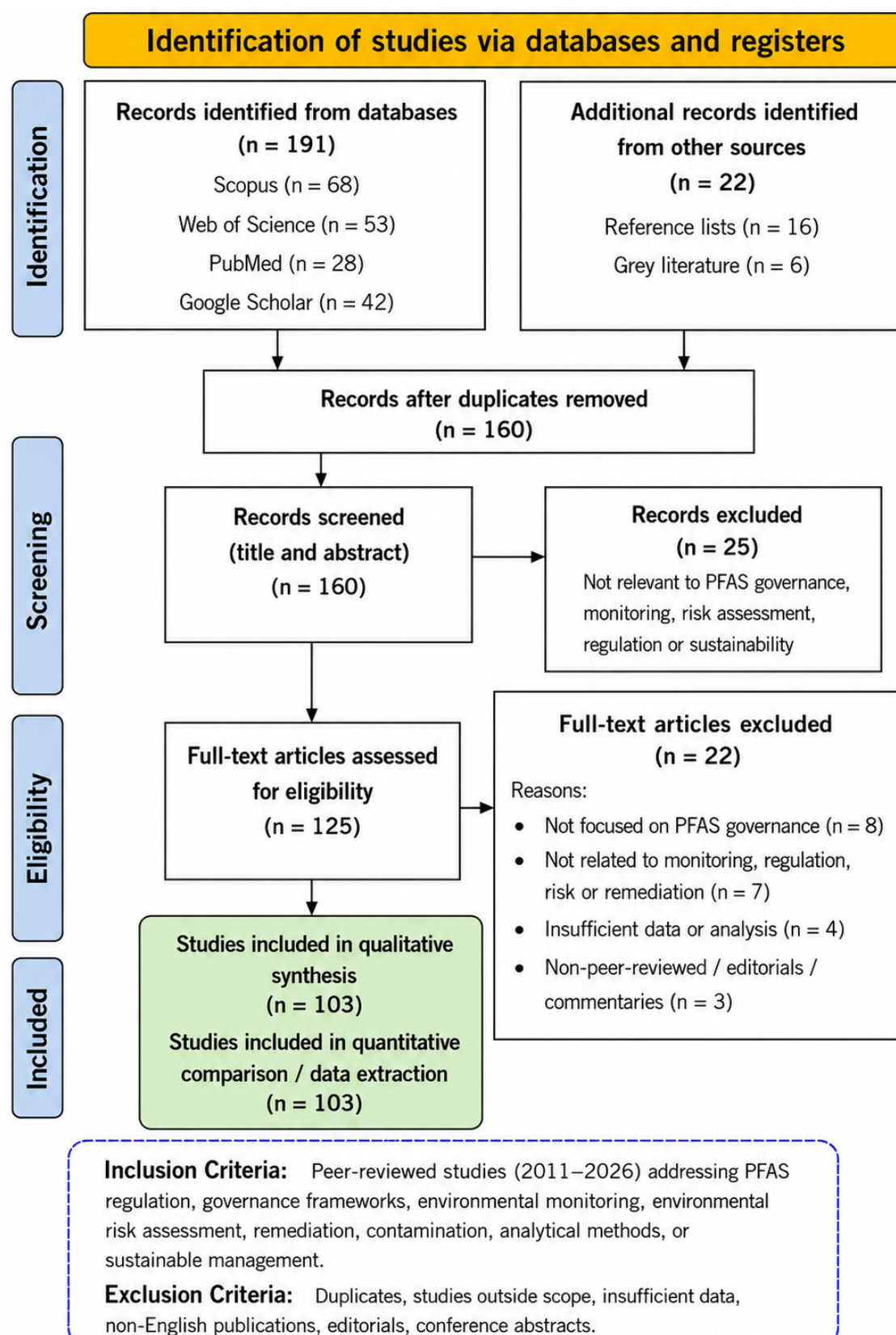
2.2. Study Selection and Eligibility

Eligible studies comprised peer-reviewed publications (2011–2026) addressing PFAS governance, regulatory frameworks, environmental occurrence, analytical methods, monitoring, risk assessment, remediation, policy development, and sustainable environmental management. Relevant international regulatory reports and policy documents were also included. Duplicate records, editorials, conference abstracts, non-English publications, and studies lacking scientific relevance were excluded. Following title, abstract, and full-text screening, 103 publications were retained for qualitative synthesis. The study selection followed a structured review approach informed by the PRISMA framework to enhance transparency and reproducibility. Figure 1 summarises the literature search and study selection process.

2.3. Data Extraction and Narrative Synthesis

Information was systematically extracted from the selected publications using a structured data extraction approach. Particular emphasis was placed on PFAS regulatory frameworks, governance strategies, environmental monitoring approaches, analytical techniques, environmental occurrence, human and ecological risk assessment, remediation technologies, policy development, and sustainable environmental management practices.

Rather than undertaking a quantitative meta-analysis, the extracted information was critically synthesised using a thematic narrative approach. The findings were organised into major themes reflecting the objectives of the review, enabling comparison of international regulatory approaches, monitoring strategies, environmental risk management practices, emerging technological developments, and future directions for sustainable PFAS governance.



Note: Numbers reflect the literature search conducted in January–July 2026.

Figure 1. PRISMA flowchart illustrating the systematic literature search, screening, eligibility assessment, and study selection process used to identify peer-reviewed publications included in this review of PFAS governance, regulatory frameworks, environmental monitoring, risk assessment, and sustainable environmental management.

2.4. Manuscript Preparation

This review was prepared through a comprehensive evaluation and critical synthesis of published scientific literature, international regulatory documents, and policy reports relating to PFAS. The authors independently interpreted the literature, developed the scientific content, and were solely responsible for the conclusions presented.

During the preparation of this manuscript, generative artificial intelligence (GenAI) tools, including ChatGPT (OpenAI, GPT-5.5), were used to support language editing, text refinement, content organisation, and readability enhancement. These tools were not used to generate scientific data, perform analyses, or formulate scientific conclusions. All AI-assisted content was critically reviewed, verified, and edited by the authors, who take full responsibility for the accuracy, integrity, and content of this manuscript.

All abbreviations have been checked and standardised throughout the manuscript and are defined at first mention in accordance with the journal's formatting requirements.

3. Sources and Environmental Occurrence of PFAS

Understanding PFAS sources provides the scientific foundation for sustainable management. Understanding the sources and transport pathways of PFAS is fundamental for identifying contamination hotspots and informing regulatory interventions. This section examines the principal sources, environmental occurrence, and transport pathways of PFAS that underpin monitoring and regulatory decision-making [12,16].

Understanding the sources and environmental occurrence of PFAS is fundamental to sustainable environmental management because it enables the identification of pollution sources, supports preventive regulatory interventions, and facilitates the development of sustainable production and waste management strategies. Characterising environmental distribution also provides the scientific basis for protecting water resources, preserving ecosystem services, reducing long-term PFAS contamination, and promoting resource-efficient approaches consistent with sustainable development and circular economy principles.

3.1. Industrial and Commercial Sources

PFAS are widely used for thermal stability, chemical resistance, hydrophobicity, and oil-repellency [1], resulting in global occurrence and concern over persistence and toxicity. Manufacturing industries are major sources, with fluorochemical facilities, electroplating, semiconductors, paper, and metal finishing releasing PFAS via wastewater, emissions, and spills [2]. Fluoropolymer synthesis and processing drive contamination hotspots, underscoring industrial contributions.

The textile industry uses fluorinated compounds in stain-resistant and water-repellent fabrics [3], with PFAS coatings applied to carpets, upholstery, clothing, and protective garments. PFAS are also used in non-stick cookware, notably polytetrafluoroethylene [6]. Food packaging, grease-resistant papers, popcorn bags, fast-food wrappers, and cardboard contain PFAS coatings], raising concerns over migration into food, dietary exposure, and long-term health risks.

PFAS are widely used in electronics for semiconductors, photography, insulation, and components due to their dielectric properties and stability [19], contributing to industrial distribution. Firefighting foams, especially AFFFs, are major global sources [20]. Extensive use at airports, military, petrochemical, and training sites causes severe PFAS contamination of soils, groundwater, and surface waters.

3.2. Environmental Distribution

PFAS persistence and widespread use have resulted in global distribution across aquatic, terrestrial, and atmospheric environments [5]. Surface waters receive inputs from industrial discharges, wastewater treatment plant (WWTP) effluents, runoff, and landfill leachate, while conventional treatment often fails to remove PFAS effectively [9,21]. Groundwater contamination is prevalent near airports, military sites, industrial facilities, and landfills, with biosolids further contributing to soil and aquifer contamination [22,23]. Atmospheric transport of volatile PFAS precursors also facilitates long-range dispersal and deposition into remote environments [24]. Figure 2 illustrates the principal PFAS transport pathways linking wastewater, surface waters, groundwater, sediments, the atmosphere, and human exposure.

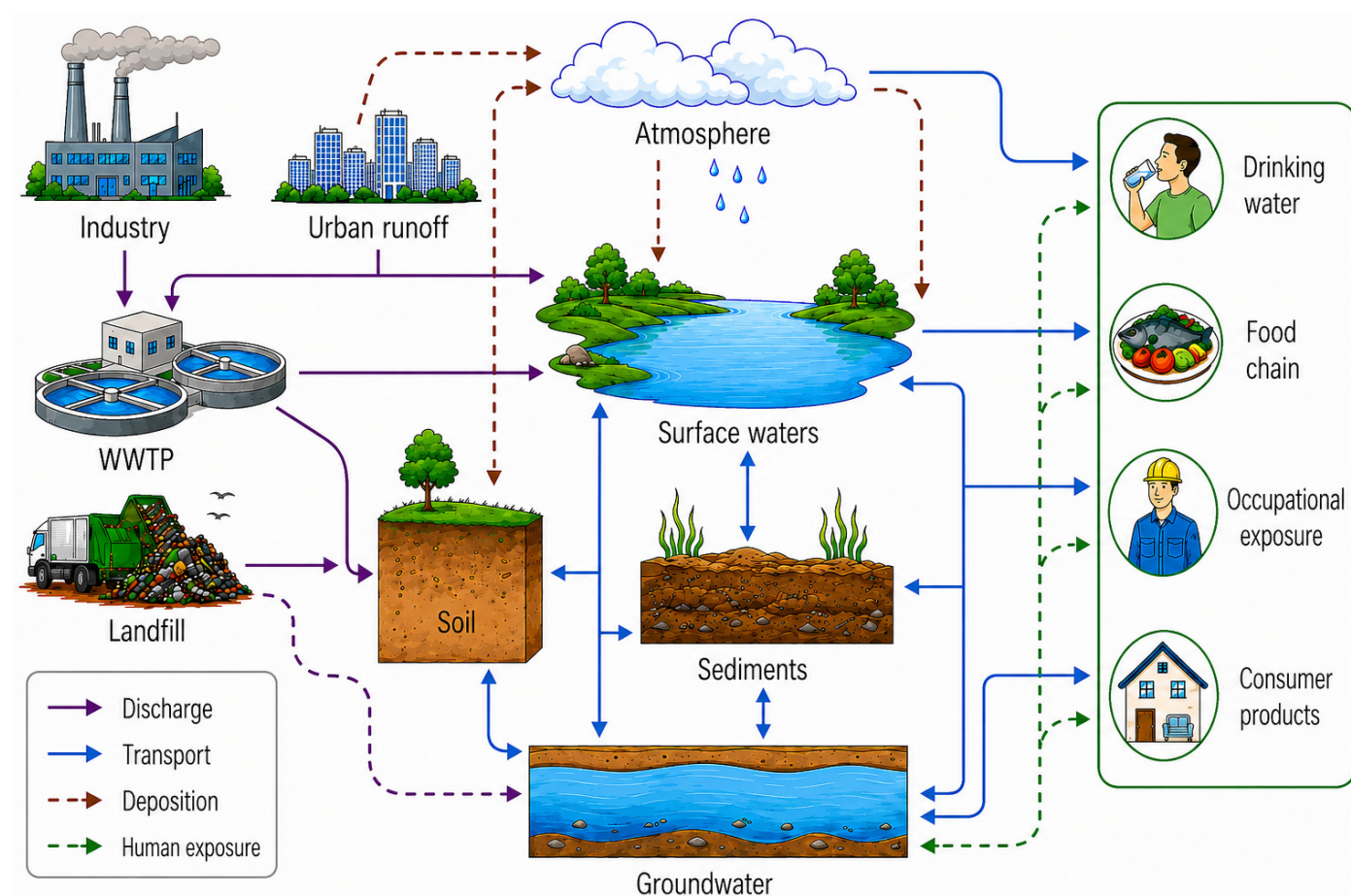


Figure 2. Conceptual illustration of the environmental transport and fate of PFAS, showing the movement of contaminants from major emission sources through wastewater treatment plants (WWTPs), surface waters, groundwater, soils, sediments, and atmospheric pathways to human exposure routes, including drinking water, food, consumer products, and occupational exposure.

3.3. Human Exposure Pathways

Human PFAS exposure occurs via multiple pathways, with drinking water a major route worldwide [14]. Contaminated groundwater and surface water elevate serum levels near industrial, military, and landfill sites. The food chain adds risks, as PFAS bioaccumulate in aquatic organisms, livestock, crops, and wildlife [4]. Aquatic food-web bioaccumulation raises persistence and biomagnification concerns.

Occupational PFAS exposure occurs in fluorochemical manufacturing, metal plating, firefighting, textiles, and waste management via inhalation, dermal contact, and ingestion [25]. Consumer products, including cookware, cosmetics, packaging, clothing, carpets,

cleaning products, and personal care, release PFAS indoors, contaminating dust [26]. Indoor exposure, especially for children, underscores widespread PFAS occurrence and highlights the need for comprehensive monitoring, risk assessment, and regulatory management strategies.

4. Toxicological and Public Health Concerns

Toxicological evidence underpins effective risk assessment and regulatory decision-making. This section examines the toxicological evidence that underpins current PFAS risk assessment and regulatory decision-making [27]. Because adverse human and ecological health effects directly influence environmental policy and public health protection, understanding PFAS toxicity is essential for developing effective risk management strategies and supporting sustainable environmental management.

4.1. Persistence and Bioaccumulation

PFAS are recognised for persistence and resistance to degradation, driven by strong carbon-fluorine bonds conferring thermal stability and resistance to chemical, biological, and photolytic breakdown [2]. Long-chain PFAS, notably PFOA and PFOS, bioaccumulate in wildlife and humans [7], concentrating in serum, liver, and organs. Bioaccumulation across aquatic food webs, mammals, fish, birds, and terrestrial organisms raises biomagnification and chronic exposure concerns [21]. Short-chain PFAS and hexafluoropropylene oxide dimer acid (HFPO-DA)-based fluoropolymer processing aid (GenX) substitutes, introduced as safer replacements, also exhibit persistence and mobility [28]. Though less bioaccumulative, their solubility and mobility enable widespread aquatic dispersion, raising ecological concerns.

4.2. Endocrine and Developmental Effects

PFAS exposure disrupts endocrine function and development in humans and wildlife [4]. Compounds affect thyroid, reproductive, and metabolic regulation. PFOA and PFOS are linked to developmental toxicity, reduced birth weight, delayed growth, altered puberty, and impaired reproduction [14,15]. Prenatal and early-life exposure via placenta and breast milk heightens developmental risks.

Experimental and epidemiological studies have further suggested associations between PFAS exposure and reproductive disorders, altered fertility, and endocrine-related diseases [15]. Emerging PFAS alternatives such as GenX chemicals have also shown evidence of developmental and hepatic toxicity in laboratory studies, raising concerns regarding the replacement of regulated PFAS with structurally similar compounds that may pose comparable risks [29].

4.3. Immunotoxicity and Carcinogenic Risks

PFAS exposure is linked to immune suppression, reduced vaccine effectiveness, and altered immune cell activity [30]. Children show diminished antibody responses, indicating immunotoxicity. Long-term exposure to PFOA and PFOS increases risks of liver damage, kidney dysfunction, lipid disorders, and cancers, especially kidney and testicular [31]. The International Agency for Research on Cancer and health agencies evaluate carcinogenic potential amid growing epidemiological and toxicological evidence. Short-chain PFAS substitutes and emerging fluorinated alternatives remain less extensively studied than PFOA and PFOS; however, recent findings suggest that some replacement compounds may also induce oxidative stress, liver toxicity, and immune-related effects [28]. These observations highlight the importance of evaluating the toxicological profiles of alternative PFAS compounds before widespread commercial adoption.

4.4. Ecological Impacts

PFAS contamination poses ecological risks due to persistence, mobility, and bioaccumulation. Aquatic ecosystems are vulnerable to inputs from wastewater, industry, leachate, and firefighting foams [5]. Exposure causes growth, reproductive, endocrine, behavioural, and survival effects in fish, amphibians, and invertebrates [32]. Bioaccumulation elevates risks for predators and wildlife.

Birds and marine mammals show elevated PFAS in tissues and serum, indicating long-range transport and widespread contamination [21]. Sediments and soils act as reservoirs, prolonging persistence and exposure. Short-chain PFAS substitutes remain highly mobile and difficult to remove [29]. Effective regulatory management and comprehensive monitoring are essential to minimise long-term ecological and public health risks.

5. Analytical Monitoring and Detection Challenges

Reliable analytical monitoring provides the scientific evidence required for PFAS exposure assessment, regulatory compliance, environmental risk assessment, and informed decision-making [33]. Consequently, advances in analytical monitoring strengthen environmental governance by enabling more effective management of PFAS contamination and supporting sustainable resource protection.

5.1. Conventional Analytical Techniques

Accurate PFAS detection is essential for environmental monitoring, exposure assessment, and regulatory compliance because their structural diversity, persistence, and ultra-trace occurrence require highly sensitive analytical techniques [34]. Liquid chromatography-tandem mass spectrometry (LC-MS/MS) remains the reference method for sensitive, compound-specific PFAS quantification in complex environmental and biological matrices [7]. Gas chromatography-mass spectrometry (GC-MS) is primarily applied to volatile PFAS and precursor compounds but requires derivatisation for ionic PFAS [35]. High-resolution mass spectrometry (HRMS) enables the identification of unknown PFAS and emerging contaminants [36]. Despite their analytical strengths, these techniques require costly instrumentation, specialised expertise, extensive sample preparation, and rigorous quality control, limiting routine application in resource-constrained settings.

5.2. Standardised Analytical Methods

Internationally standardised analytical methods are fundamental for ensuring comparability of PFAS monitoring data across laboratories and regulatory jurisdictions. Drinking-water monitoring in the United States is primarily conducted using U.S. EPA Methods 537.1 and 533, whereas EPA Method 1633 is applied to a broader range of environmental matrices, including surface water, groundwater, wastewater, soils, sediments, biosolids, landfill leachate, and biological tissues. Standardised methods specify requirements for sample collection, extraction, chromatographic separation, calibration procedures, quality assurance, and data validation, thereby improving analytical consistency and supporting regulatory compliance. Continued harmonisation with ISO and other internationally recognised analytical standards will further facilitate global comparability of PFAS monitoring programmes.

5.3. Emerging Screening Technologies

Growing concern over PFAS contamination has driven rapid, cost-effective, field-deployable screening technologies for environmental monitoring. These approaches complement mass spectrometry by enabling faster screening and broader detection. Figure 3 compares analytical techniques for PFAS detection and characterisation, highlighting principles, advantages, and limitations of LC-MS/MS, GC-MS, and HRMS approaches.

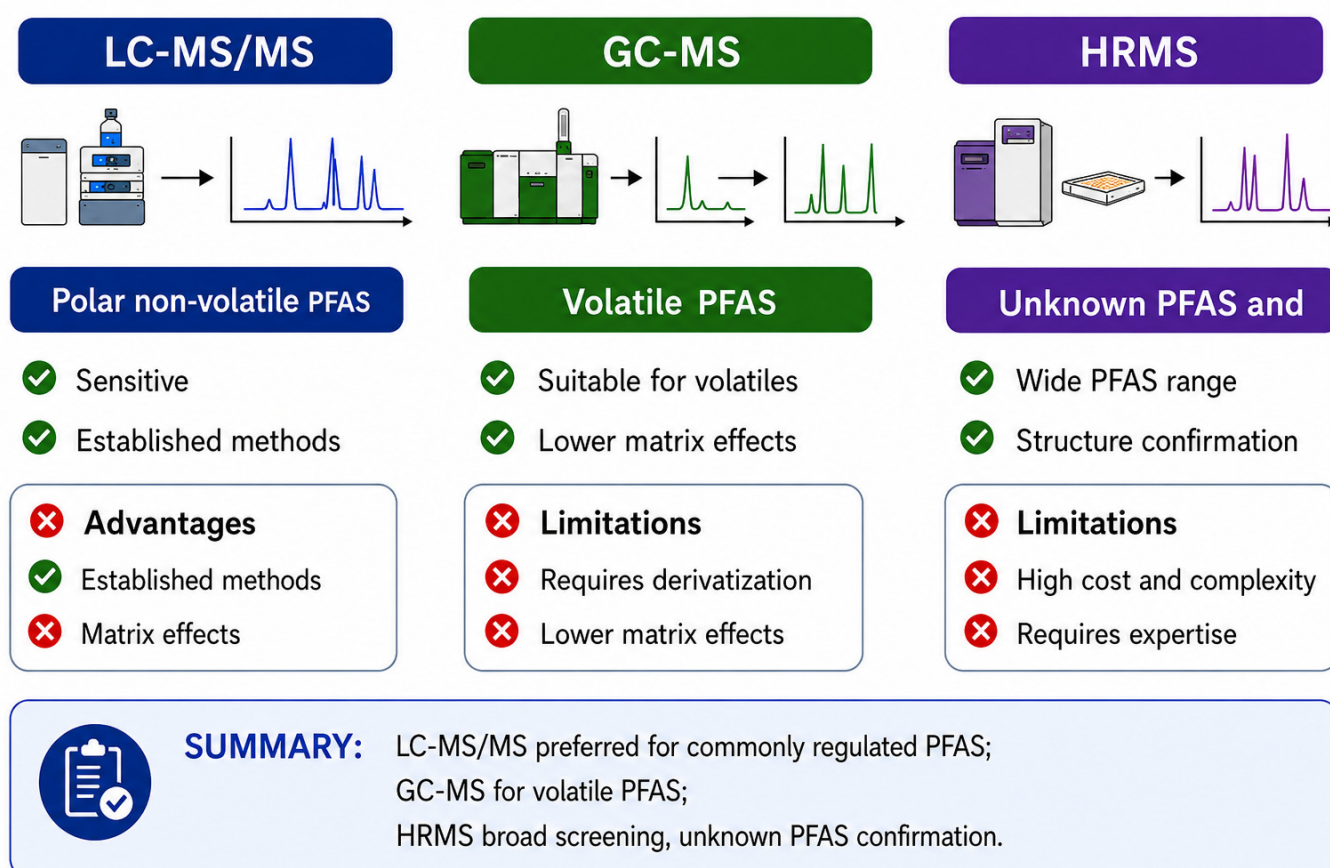


Figure 3. Comparative overview of conventional analytical techniques used for PFAS determination, including liquid chromatography-tandem mass spectrometry (LC-MS/MS), gas chromatography-mass spectrometry (GC-MS), and high-resolution mass spectrometry (HRMS), highlighting their analytical applications, strengths, limitations, and suitability for targeted and non-target PFAS analysis. Green check marks (✓) indicate key strengths or favourable analytical characteristics, whereas red crosses (X) denote analytical limitations or challenges associated with each technique.

Fluorescence-based methods, including spectroscopy, excitation-emission matrix analysis, and sensor-assisted techniques, provide sensitive and relatively simple approaches for PFAS monitoring [37]. Electrochemical, optical, biosensor, and nanomaterial-based platforms enable portable, real-time environmental surveillance with reduced costs [38]. Non-target screening has become increasingly important because thousands of fluorinated compounds remain analytically uncharacterised [2]. High-resolution mass spectrometry, advanced data processing, chemometrics, and machine learning further enhance the identification of unknown PFAS, transformation products, and emerging substitutes [36]. Table 1 compares conventional and emerging PFAS

analytical technologies, highlighting their analytical scope, principal advantages, limitations, and suitability for different environmental monitoring objectives.

Table 1. Comparison of conventional and emerging analytical monitoring technologies used for PFAS detection, summarising their analytical principles, target compounds, analytical sensitivity, major advantages, limitations, and typical environmental applications for regulatory monitoring, environmental surveillance, and research.

Technology	Target PFAS	Advantages	Limitations	Applications
LC-MS/MS	Polar, non-volatile PFAS	High sensitivity; quantitative; regulatory standard	Expensive; targeted compounds only	Drinking water, wastewater, food, biological samples
GC-MS	Volatile PFAS and precursors	Good separation; suitable for volatile compounds	Derivatisation required; limited PFAS coverage	Industrial emissions, precursor analysis
HRMS	Known and unknown PFAS	Non-target screening; identifies emerging PFAS	High cost; complex data analysis	Environmental surveillance, research
Fluorescence	Selected PFAS	Rapid; simple; inexpensive	Lower selectivity	Preliminary environmental screening
Electrochemical sensors	Selected PFAS	Portable; rapid; field deployable	Matrix interference	On-site water monitoring
Biosensors	Specific PFAS	High specificity; rapid detection	Limited stability	Drinking water monitoring
Nanomaterial sensors	Selected PFAS	Enhanced sensitivity	Still under development	Emerging monitoring technologies
Non-target screening	Unknown PFAS	Comprehensive chemical profiling	Computationally intensive	Discovery of novel PFAS
EOF/AOF analysis	Total organofluorine	Measures unidentified PFAS burden	Does not identify individual compounds	Screening total PFAS contamination
TOP assay	PFAS precursors	Detects hidden precursor contamination	Semi-quantitative	Site investigations, remediation studies

Abbreviations: AOF, Adsorbable Organic Fluorine; EOF, Extractable Organic Fluorine; GC-MS, Gas Chromatography-Mass Spectrometry; HRMS, High-Resolution Mass Spectrometry; LC-MS/MS, Liquid Chromatography-Tandem Mass Spectrometry; PFAS, Per- and Polyfluoroalkyl Substances; TOP, Total Oxidisable Precursor (assay).

5.4. Practical Considerations for PFAS Monitoring Programmes

Selecting an appropriate PFAS analytical technique requires balancing analytical performance, cost, operational complexity, and monitoring objectives. LC-MS/MS and HRMS remain the reference methods for sensitive, compound-specific PFAS identification and quantification but require costly instrumentation and specialised expertise [7]. Emerging technologies, including fluorescence-based sensors, electrochemical sensors, biosensors, and other portable platforms, provide rapid, cost-effective screening but still require laboratory confirmation for regulatory compliance [38,39]. Effective monitoring also depends on adequate analytical infrastructure, trained personnel, harmonised methodologies, and robust quality assurance and quality control (QA/QC) systems. Standardised sampling, validated analytical methods, certified reference materials, isotope-labelled internal standards, and inter-laboratory proficiency testing improve

analytical reliability and support harmonised environmental standards [33]. Furthermore, stringent contamination control during sampling and analysis, including the use of PFAS-free materials, polyethylene or polypropylene containers, rigorous laboratory cleaning, and clean-room practices, minimises background contamination and enhances data quality [33,40]. Collectively, these measures strengthen evidence-based PFAS monitoring and environmental governance.

5.5. Challenges in PFAS Quantification

Despite advances, PFAS quantification remains challenging because of their structural diversity, ultra-trace occurrence, and complex environmental matrices, requiring highly sensitive instrumentation, contamination-free procedures, and rigorous quality assurance [14,15]. Routine analytical methods target mainly PFOA and PFOS, leaving many emerging PFAS and transformation products poorly characterised owing to limited certified reference standards [19,36]. Matrix effects in wastewater, sediments, biosolids, and biological samples further compromise analytical accuracy [34]. Continued improvements in analytical sensitivity, method standardisation, non-target screening, and portable sensing technologies are essential for effective monitoring and risk assessment.

5.6. Detection Limitations and Emerging Analytical Challenges

Despite major advances in PFAS analytical chemistry, technical limitations continue to constrain comprehensive environmental monitoring. Conventional LC-MS/MS methods primarily quantify well-characterised PFAS such as PFOA and PFOS, whereas thousands of structurally diverse PFAS remain difficult to detect because of limited reference standards, validated analytical methods, and toxicological data [7]. Short-chain and ultra-short-chain PFAS present additional analytical challenges because of their high solubility, mobility, and polarity, which reduce extraction efficiency and chromatographic retention [36]. Furthermore, precursor compounds and transformation products may escape targeted analysis, making complementary approaches such as the total oxidisable precursor (TOP) assay essential for more comprehensive assessment [41]. High-resolution mass spectrometry, suspect screening, and non-target analysis improve detection of unknown PFAS but remain constrained by limited spectral libraries and analytical standards [36,42]. Matrix effects, incomplete extraction, and limited certified reference materials further compromise analytical accuracy, highlighting the need for harmonised methods, improved QA/QC, and integrated targeted and non-target workflows to strengthen evidence-based PFAS monitoring and regulation [34].

5.7. PFAS Monitoring Strategies

Effective PFAS governance and environmental risk management depend on comprehensive monitoring strategies capable of identifying contamination sources, tracking environmental distribution, assessing human exposure, and evaluating regulatory effectiveness. While advances in analytical chemistry have substantially improved PFAS detection, monitoring programmes must incorporate strategic sampling frameworks that address diverse environmental compartments and exposure pathways. Consequently, PFAS monitoring has evolved from targeted analytical measurements to integrated surveillance systems that support risk assessment, regulatory compliance, and long-term environmental stewardship [19,43].

5.7.1. Drinking-Water Monitoring and Regulatory Compliance

Drinking water is a major PFAS exposure pathway and therefore a global monitoring priority. Routine surveillance supports contaminant detection, treatment evaluation, and

compliance with increasingly stringent standards [14,15,44]. Regulatory agencies in the United States, European Union (EU), Canada, and Australia have introduced lower guideline values [44,45]. Targeted LC-MS/MS quantifies priority PFAS, including PFOA and PFOS, while complementary screening approaches detect emerging compounds [46]. Long-term monitoring programmes support exposure assessment, risk evaluation, and evidence-based regulatory decision-making.

5.7.2. Groundwater Monitoring near Airports and Military Installations

Groundwater monitoring is essential in areas impacted by AFFF use. Airports, military bases, fire-training sites, and emergency response facilities represent major PFAS hotspots because of decades of foam application [20,22]. PFAS migrate through soils into aquifers, resulting in persistent contamination of drinking-water resources. Monitoring networks characterise contaminant plumes, identify sources and migration pathways, and provide temporal data to support remediation, regulatory compliance, and risk management [5].

5.7.3. Wastewater Monitoring and Industrial Surveillance

WWTPs receive PFAS from industrial discharges, municipal wastewater, landfill leachates, and consumer product residues and may also act as secondary contamination sources because many PFAS are incompletely removed during treatment [8,47]. Monitoring programmes evaluate contaminant sources, treatment performance, and environmental emissions, while industrial surveillance supports regulatory compliance in fluorochemical manufacturing, metal plating, textile, paper, and semiconductor industries. Increasingly, wastewater monitoring is integrated into regulatory frameworks to identify emerging PFAS and evaluate pollution-control measures [43].

5.7.4. Environmental Surveillance of Surface Waters, Sediments, and Biota

Environmental surveillance extends beyond drinking water and wastewater to rivers, lakes, estuaries, sediments, and biota. Surface-water monitoring identifies contaminant transport pathways, hotspots, and ecosystem exposure [5]. Sediment monitoring provides information on historical contamination and long-term persistence [48]. Biota monitoring evaluates bioaccumulation, trophic transfer, and ecological exposure using fish, invertebrates, birds, and marine mammals as sentinel species to assess PFAS distribution within food webs and associated ecological and human health risks [49].

5.7.5. Emerging Monitoring Approaches

Advances in analytical science have expanded PFAS monitoring beyond conventional targeted analysis. HRMS-based suspect screening and non-target workflows facilitate detection of unknown PFAS and transformation products [36,42]. Total organic fluorine techniques complement targeted LC-MS/MS by estimating the overall burden of organofluorine compounds in environmental samples. Extractable organic fluorine (EOF) quantifies extractable fluorinated substances, whereas adsorbable organic fluorine (AOF) measures organofluorine compounds retained on activated carbon. Comparing targeted PFAS concentrations with EOF or AOF measurements enables estimation of unidentified organofluorine fractions, including emerging PFAS, transformation products, and previously uncharacterised fluorinated compounds [50]. Similarly, the TOP assay converts oxidisable PFAS precursors into measurable perfluoroalkyl acids, revealing hidden contamination that would otherwise remain undetected by targeted analysis [41]. Passive sampling technologies provide cost-effective, time-integrated measurements, improving spatial coverage and long-term surveillance of aquatic and groundwater

systems [51]. Collectively, these complementary approaches strengthen understanding of PFAS occurrence, transformation, and environmental fate while supporting flexible governance frameworks, risk assessment, and global management strategies.

5.8. Interrelationships Between Monitoring, Risk Assessment, and Regulation

Environmental monitoring, risk assessment, and regulatory decision-making are closely interconnected components of effective PFAS governance. Reliable monitoring provides the scientific evidence required to identify PFAS contamination sources, quantify environmental concentrations, evaluate human exposure, and support regulatory compliance. Conversely, inadequate monitoring capacity limits the availability of high-quality exposure data, increases uncertainty in risk assessment, and weakens the scientific basis for establishing protective regulatory standards. These limitations may delay regulatory action, reduce enforcement effectiveness, and hinder the identification of emerging PFAS contaminants. Strengthening analytical capacity, expanding long-term environmental monitoring programmes, and improving data sharing among regulatory authorities are therefore essential for supporting evidence-based policy development and responsive environmental governance.

6. Global Regulatory Frameworks for PFAS

The analytical evidence generated through environmental monitoring provides the scientific foundation for the development and continual refinement of contemporary PFAS regulatory frameworks. These frameworks translate scientific evidence into practical environmental protection measures by establishing monitoring requirements, health-based guideline values, regulatory standards, and risk management strategies designed to protect human health and the environment [10,52]. In response to the scientific evidence reviewed in the preceding sections, governments worldwide have developed regulatory frameworks. Because PFAS regulations continue to evolve rapidly, the discussion presented below reflects the regulatory status and legislative developments available at the time of manuscript revision. Governments and environmental agencies have increasingly introduced policies, drinking water standards, monitoring requirements, and restrictions aimed at controlling PFAS production, use, and environmental release [53]. However, substantial differences remain in the scope, stringency, and implementation of PFAS regulations among countries, reflecting varying scientific, economic, and policy priorities.

Effective regulatory frameworks are fundamental to sustainable chemical management because they promote pollution prevention, encourage responsible industrial practices, strengthen environmental accountability, and protect natural resources for future generations. The progressive evolution of PFAS regulations therefore represents an important component of sustainable environmental governance and international efforts to minimise chemical risks while supporting sustainable economic development.

6.1. United States Regulatory Framework

The U.S. is a leading jurisdiction in PFAS regulation, with oversight by the Environmental Protection Agency (EPA), the Food and Drug Administration (FDA), and state agencies [54]. Recent EPA actions, including enforceable drinking-water standards for PFOA and PFOS, reflect growing concern over PFAS contamination and public health risks [55,56]. Several states, including New Jersey, Michigan, California, and Vermont, have adopted even stricter standards [22]. The designation of PFAS as hazardous substances under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and expanded authorities under the Toxic Substances Control Act

(TSCA) have strengthened reporting, remediation, and industrial oversight [56,57]. The FDA has supported PFAS phase-outs in food packaging [58], while state-level initiatives have expanded environmental monitoring, discharge controls, cleanup standards, biosolids management, and product restrictions, often responding more rapidly to local contamination [59].

6.2. European Union Regulations

The European Union has established one of the world's most comprehensive PFAS regulatory frameworks through REACH, the Drinking Water Directive, and broader chemical safety legislation [45]. REACH requires manufacturers and importers to provide information on PFAS production, use, toxicity, and environmental behaviour, while restricting hazardous compounds such as PFOS and PFOA [60]. Recognising the limitations of compound-specific regulation, the European Chemicals Agency has proposed class-based restrictions covering thousands of PFAS to reduce regrettable substitution and strengthen preventive chemical management [61]. The Drinking Water Directive further requires routine monitoring and establishes quality standards for PFAS in drinking water [62]. Complementary initiatives under the European Green Deal and Zero Pollution Action Plan promote PFAS substitution, reduced industrial emissions, sustainable chemical design, and enhanced environmental surveillance, reinforcing long-term environmental protection and sustainable chemical management [60].

6.3. International Agreements

International agreements strengthen PFAS governance by promoting coordinated responses to their global transport and environmental occurrence. The Stockholm Convention on Persistent Organic Pollutants provides the principal international framework for restricting hazardous PFAS, including PFOS and PFOA, thereby reinforcing global regulatory cooperation [43]. The Organisation for Economic Co-operation and Development (OECD) further supports PFAS management through harmonised terminology, risk assessment frameworks, analytical methodologies, and international information sharing [19]. Complementary initiatives under the Strategic Approach to International Chemicals Management (SAICM), the United Nations Environment Programme (UNEP), and global monitoring programmes strengthen scientific understanding and regulatory coordination [43]. Nevertheless, substantial differences in regulatory standards, monitoring capacity, analytical infrastructure, and legislative priorities continue to influence the effectiveness of PFAS governance across jurisdictions [52].

6.4. Regulatory Developments in Other Regions

Several countries beyond the U.S. and EU have introduced PFAS regulatory frameworks, although implementation varies considerably. Canada regulates PFAS through Health Canada and Environment and Climate Change Canada, supported by drinking-water guidelines and environmental monitoring programmes [63]. Australia addresses PFAS through the National Environmental Management Plan, focusing on site assessment, monitoring, remediation, and health risk management [64]. China has strengthened industrial discharge monitoring and regulatory oversight [65], while Japan has expanded drinking-water monitoring and regulation following contamination incidents [66]. South Africa currently lacks comprehensive PFAS-specific legislation but is increasing environmental monitoring and policy development [67].

Although PFAS governance has advanced in several developed jurisdictions, it remains comparatively limited across much of Latin America, Africa, and South and Southeast Asia, where comprehensive legislation, routine environmental monitoring, and

enforceable drinking-water standards are often absent or still developing. Regulatory implementation is constrained by limited analytical infrastructure, technical capacity, and financial resources. Nevertheless, international collaboration through the Stockholm Convention, OECD, and UNEP is strengthening capacity building, technology transfer, and national PFAS management frameworks [68–70]. Table 2 provides a quantitative comparison of international PFAS governance, summarising drinking-water limits, regulated PFAS, monitoring, enforcement, reporting requirements, polluter-pays provisions, and governance maturity to highlight differences in regulatory implementation and effectiveness across major jurisdictions.

Table 2. Quantitative comparison of PFAS governance across major international jurisdictions, summarising drinking-water limits, regulated PFAS, monitoring requirements, enforcement mechanisms, reporting obligations, polluter-pays provisions, and governance maturity.

Country/Region	Drinking-Water Limit *	Regulated PFAS Compounds	Monitoring	Enforcement	Reporting	Polluter-Pays	Governance
USA	PFOA 4; PFOS 4 ng/L [71]	6	Routine	Strong	Yes	Yes (CERCLA)	High
EU	Σ20 PFAS 100; Total PFAS 500 ng/L [72]	20 +	Routine	Strong	Yes	Yes	Very High
Canada	ΣSelected PFAS 30 ng/L [73]	Multiple	Routine	Moderate-Strong	Yes	Partial	High
China	PFOA: 80 ng/L; PFOS: 40 ng/L (reference values) [74]	Priority PFAS	Developing	Moderate	Yes	Partial	Developing
Australia	PFOS+PFHxS 200; PFOA 560 ng/L [75]	Priority PFAS	Periodic	Moderate	Yes	Partial	Moderate
Japan	PFOS+PFOA 50 ng/L [76]	2 (expanding)	Routine	Moderate	Partial	Limited	Moderate
South Africa	No PFAS-specific standard	None	Limited	Limited	No	No	Early stage
Latin America	Country-dependent (generally absent)	Limited	Developing	Limited	Partial	Limited	Emerging
South and Southeast Asia	Country-specific (emerging)	Limited-Moderate	Developing	Moderate	Partial	Partial	Emerging

* Drinking-water values represent legally enforceable standards, reference indicator values, guideline values, or health-based objectives, depending on the jurisdiction. † Twenty PFAS are regulated under the EU Drinking Water Directive (EU 2020/2184), while broader class-based restrictions continue to be evaluated under the REACH restriction proposal. Abbreviations: CERCLA, Comprehensive Environmental Response, Compensation, and Liability Act; EU, European Union; PFAS, per- and polyfluoroalkyl substances; PFHxS, perfluorohexane sulphonate; PFOA, perfluorooctanoic acid; PFOS, perfluorooctane sulphonate; REACH, Registration, Evaluation, Authorisation and Restriction of Chemicals; USA, United States of America.

The comparison reveals several important trends in global PFAS governance. The U.S., EU, and Australia have established comparatively robust governance systems

characterised by strong environmental monitoring programmes, drinking-water standards, and remediation frameworks [71,72,75]. The EU has adopted the most advanced class-based regulatory approach, whereas the U.S. and Canada continue to rely primarily on risk-based management of selected PFAS compounds. In contrast, Japan remains in an emerging phase of PFAS governance, while South Africa faces challenges associated with limited monitoring capacity, regulatory development, and remediation infrastructure. These differences highlight the need for greater international harmonisation, capacity building, and knowledge transfer to support more consistent and effective PFAS management globally.

6.5. Emerging PFAS Governance in Developing Regions

Although PFAS governance has advanced considerably in North America, Europe, Australia, and Japan, regulatory development remains limited across many parts of Latin America, Africa, and South and Southeast Asia. In these regions, comprehensive PFAS legislation, environmental monitoring programmes, and legally enforceable drinking-water standards are often absent or still developing, constrained by limited analytical capacity, financial resources, and institutional infrastructure. Consequently, information on PFAS occurrence and exposure remains fragmented. Nevertheless, growing international awareness is driving gradual regulatory progress through strengthened chemical management legislation, expanded monitoring programmes, and participation in initiatives led by organisations such as the OECD [19,43]. Future progress will depend on sustained investment in analytical infrastructure, technical capacity, harmonised monitoring methodologies, and internationally coordinated regulatory frameworks to promote equitable PFAS governance, environmental justice, and reduced disparities in environmental protection.

6.6. The Global Plastics Treaty and PFAS Governance

The Global Plastics Treaty is a major international initiative promoting life-cycle management of plastics and associated chemical contaminants, including PFAS, through strengthened international cooperation, environmental monitoring, risk assessment, harmonised reporting, and capacity building [77]. Increasing recognition of PFAS as hazardous plastic additives reinforces the need for coordinated management across the plastics value chain and supports a life-cycle approach to PFAS governance [61,78,79]. Figure 4 presents an integrated PFAS governance framework linking environmental monitoring, innovation, policy, institutions, and adaptive management. Successful implementation will require international consensus, effective compliance mechanisms, financial and technical support, and continued international collaboration [78].

Previous international agreements, including the Stockholm Convention on Persistent Organic Pollutants and the Minamata Convention on Mercury, demonstrate that legally binding multilateral treaties can substantially reduce global emissions of hazardous substances when supported by robust environmental monitoring, technical assistance, and sustained political commitment. These precedents provide valuable lessons for future international PFAS governance [80–82].

6.7. Critical Comparison of Global PFAS Governance Frameworks

Although significant progress has been achieved in PFAS governance, important differences remain in regulatory scope, enforcement, environmental monitoring, and adoption of precautionary approaches. Among major jurisdictions, the European Union has adopted one of the most comprehensive governance frameworks by increasingly regulating PFAS as a chemical class under REACH, thereby reducing the risk of regrettable substitution. In contrast, the U.S. has historically relied on compound-specific,

risk-based regulation, although recent EPA actions indicate movement towards broader management [10,83]. Canada and Australia maintain robust environmental monitoring programmes but continue to rely primarily on risk-based regulation [73,75], whereas developing countries, including South Africa, face implementation challenges related to limited analytical capacity and resources. Consequently, PFAS governance remains dynamic, requiring continued regulatory adaptation, international cooperation, and strengthened monitoring capacity.

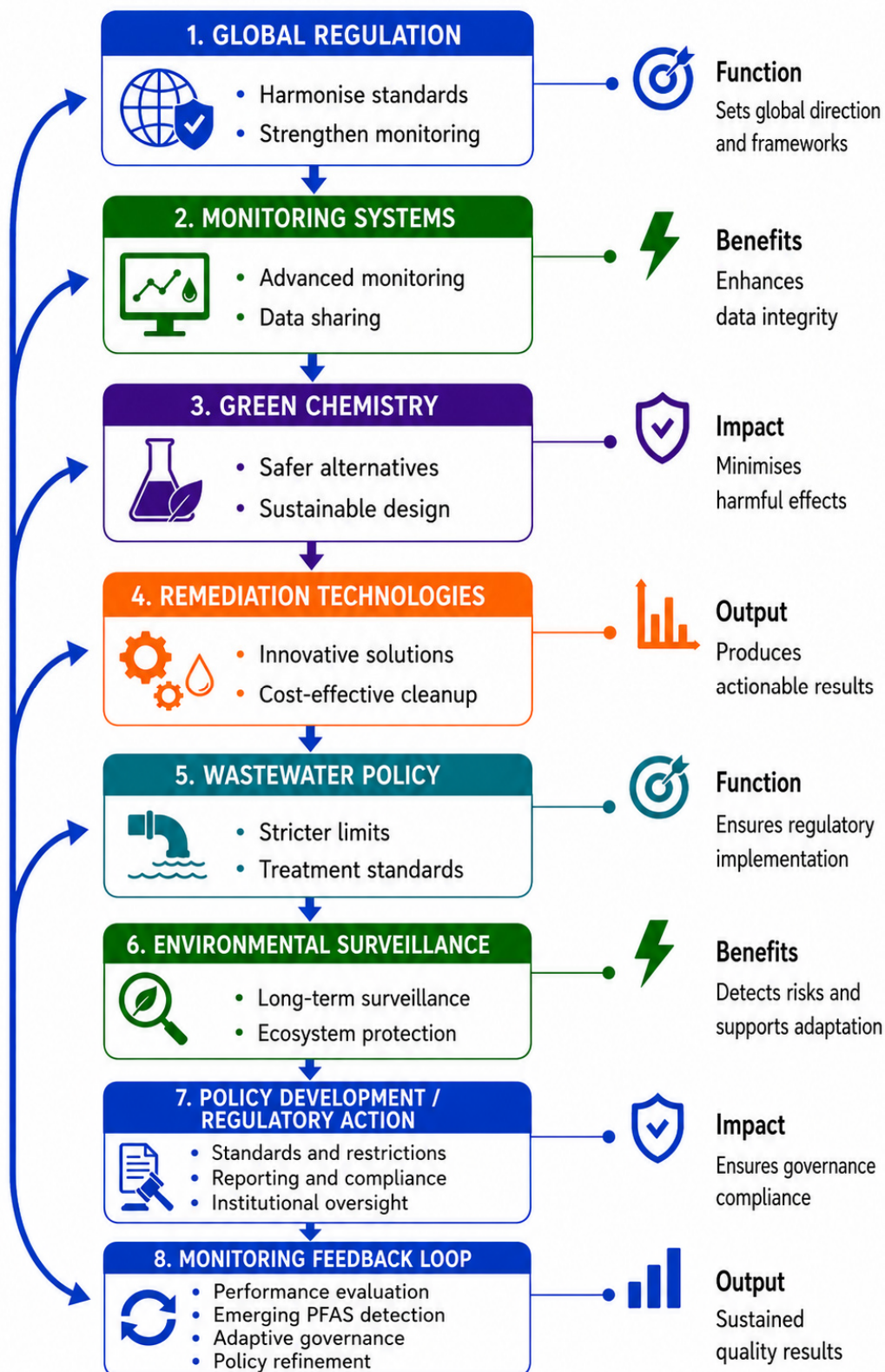


Figure 4. Integrated environmental safety roadmap for PFAS governance and management. The figure illustrates a sequential framework linking global regulation, environmental monitoring, green chemistry, remediation technologies, wastewater policy, environmental surveillance, and policy development with regulatory action.

7. Policy Responses and Risk Management Strategies

Risk assessment plays a central role in prioritising PFAS remediation strategies and resource allocation by integrating environmental and human health risks with evidence-based management [84]. Overall, PFAS governance is evolving towards more comprehensive and preventive regulatory frameworks, although substantial differences remain in regulatory scope, implementation, and enforcement. While the EU has largely adopted a precautionary, class-based approach, the U.S., Canada, Australia, and Japan continue to rely primarily on risk-based frameworks that expand as new scientific evidence emerges [71–73,75,76]. Across jurisdictions, effective governance consistently depends on robust environmental monitoring, science-based risk assessment, transparent reporting, stakeholder engagement, and adaptive policy development. However, countries with developing regulatory systems continue to face challenges related to limited analytical capacity, fragmented legislation, and resource constraints, underscoring the need for international collaboration, harmonised standards, and technology transfer to strengthen global PFAS governance.

To facilitate a critical comparison of international PFAS governance approaches, Table 3 summarises the principal regulatory characteristics of selected jurisdictions, including governance approaches, class-based regulation, environmental monitoring requirements, drinking-water limits, remediation frameworks, and the principal legislative or policy instruments supporting PFAS management. The comparison highlights both the common elements and the remaining differences in international PFAS governance, providing insight into evolving regulatory priorities and opportunities for strengthening sustainable environmental management.

Table 3. Comparative overview of PFAS governance frameworks across major international jurisdictions, summarising governance approaches, class-based regulation, monitoring requirements, drinking-water limits, remediation frameworks, and the principal legislative instruments supporting PFAS management.

Region	Approach	Class	Monitoring	Water Limits	Remediation	Key Framework
USA	Risk-based	Partial	Strong	Yes	Strong	CERCLA, TSCA, SDWA
EU	Hazard-based	Yes	Strong	Yes	Strong	REACH, Drinking Water Directive
Canada	Risk-based	Developing	Moderate	Yes	Moderate	CEPA, Health Canada
China	Emerging risk-based	Limited	Developing Strong	Yes (guideline values)	Developing	Chemical Laws, Stockholm Execution
Australia	Site-focused	Limited	Strong	Yes	Strong	NEMP
Japan	Emerging	Limited	Moderate	Yes	Moderate	Drinking Water Guidelines
South Africa	Early stage	No	Limited	Limited	Limited	No PFAS-specific legislation
Latin America	Emerging	Limited	Limited-Developing	Mostly Absent	Developing	National Stockholm Regulation

South and Southeast Asia	Emerging	Limited	Developing	Variable	Developing	National Stockholm Regulation
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Abbreviations: CEPA, Canadian Environmental Protection Act; CERCLA, Comprehensive Environmental Response, Compensation, and Liability Act; EU, European Union; NEMP, National Environmental Management Plan; PFAS, Per- and Polyfluoroalkyl Substances; REACH, Registration, Evaluation, Authorisation and Restriction of Chemicals; TSCA, Toxic Substances Control Act.

The comparison presented in Table 2 demonstrates that effective PFAS governance depends not only on regulatory standards but also on comprehensive environmental monitoring, analytical capacity, enforcement, institutional strength, and sustained scientific investment [19,52]. The EU and the U.S. have generally achieved stronger governance outcomes through robust monitoring systems, established regulatory institutions, and continual policy updates informed by emerging scientific evidence. In contrast, jurisdictions with limited monitoring infrastructure, analytical capacity, and institutional resources often experience slower regulatory implementation. The comparison further shows that governance instruments serve complementary roles: drinking-water standards reduce exposure, class-based regulation limits regrettable substitution, environmental monitoring supports evidence-based decision-making, and polluter-pays and product stewardship mechanisms promote pollution prevention and industry accountability despite continuing implementation challenges.

Although significant progress has been made in strengthening PFAS governance worldwide, regulatory effectiveness continues to vary among jurisdictions. Countries with comprehensive environmental monitoring, enforceable drinking-water standards, robust compliance mechanisms, and sustained scientific investment have generally achieved greater success in identifying contaminated sites, reducing human exposure, and improving risk management. Conversely, fragmented regulatory systems and limited analytical capacity continue to constrain effective PFAS management. These observations demonstrate that successful governance depends on institutional capacity, stakeholder collaboration, enforcement, and long-term scientific investment in addition to regulatory stringency. From a sustainability perspective, preventive strategies based on cleaner production, sustainable product design, and responsible chemical management are essential for reducing future PFAS releases. Figure 5 compares the principal international PFAS governance frameworks and policy priorities.

7.1. Comparative Evaluation of International PFAS Governance Frameworks

Although PFAS governance has advanced considerably, regulatory effectiveness continues to vary because of differences in regulatory philosophy, institutional capacity, environmental monitoring, and enforcement. The EU has adopted one of the most comprehensive approaches through progressive class-based restrictions under REACH, reducing regrettable substitution and promoting sustainable chemical management, although implementation requires substantial scientific evidence and regulatory capacity [85,86]. In contrast, the U.S. has traditionally relied on compound-specific, risk-based regulation, but recent developments, including the EPA National Primary Drinking Water Regulation (2024), stronger environmental monitoring, and CERCLA enforcement, indicate a shift towards broader management [87]. These contrasting approaches illustrate the balance between precautionary regulation and evidence-based risk assessment [83,86]. Canada and Australia have strengthened PFAS management through science-based monitoring, contaminated-site management, and progressive regulatory reforms [73,75], whereas Japan continues to expand its regulatory oversight. South Africa remains at an

earlier stage of PFAS governance because of limited analytical capacity, monitoring infrastructure, and regulatory standards [76]. Overall, effective PFAS governance depends not only on stringent regulation but also on scientific research, analytical capacity, routine monitoring, stakeholder engagement, effective enforcement, and international collaboration to achieve sustainable environmental management.

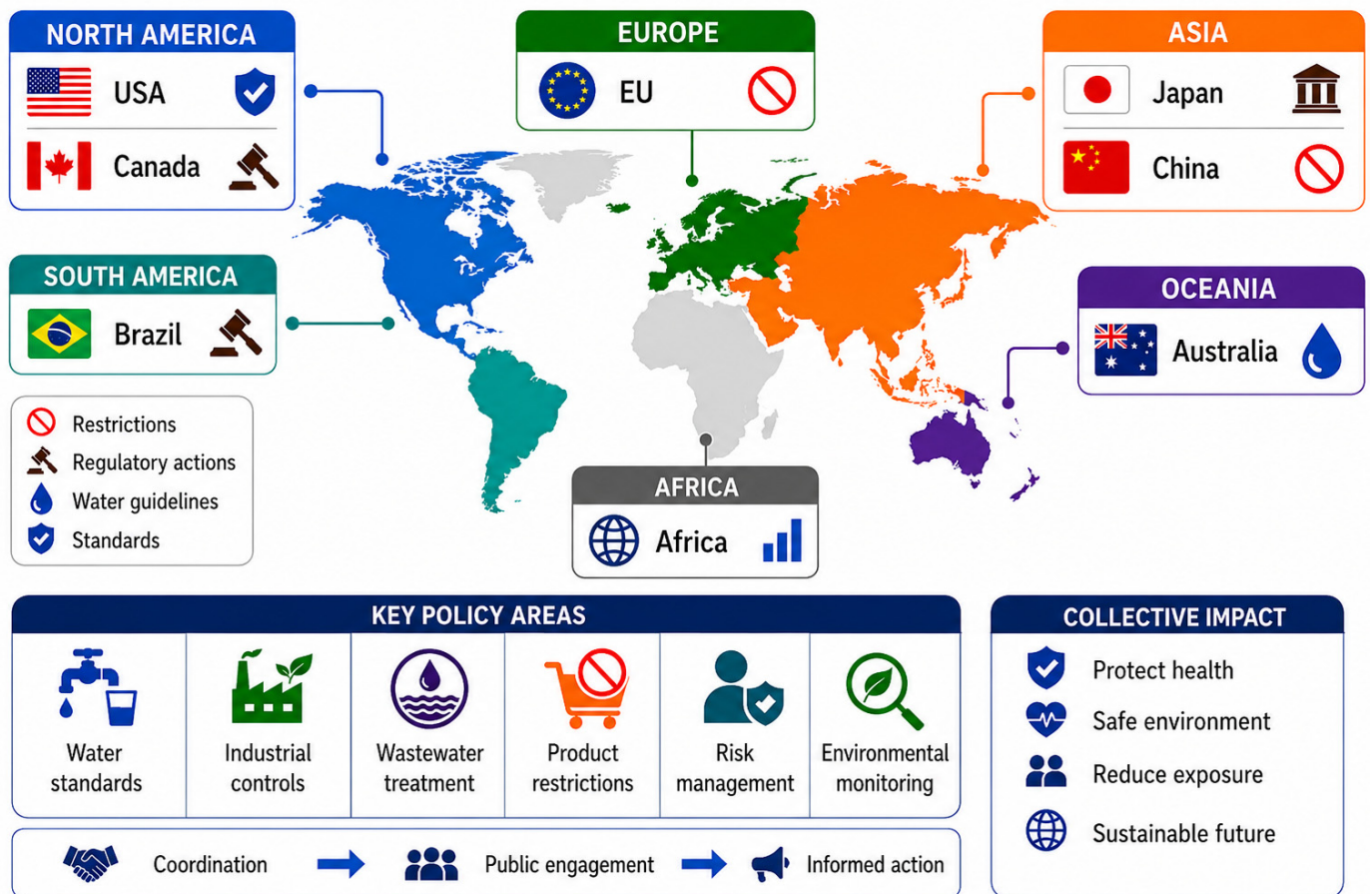


Figure 5. Global comparison of PFAS regulatory frameworks and policy responses across major international regions, highlighting regional differences in regulatory priorities, governance instruments, drinking-water protection, environmental monitoring, restrictions, and policy implementation strategies that collectively support PFAS risk management and sustainable environmental management.

7.2. Governance Effectiveness of International PFAS Regulatory Frameworks

Evaluating PFAS governance requires consideration of measurable outcomes beyond policy adoption, including reductions in environmental contamination, improved monitoring, remediation of contaminated sites, enhanced public health protection, and strengthened regulatory compliance. Although environmental recovery remains challenging because of PFAS persistence, several jurisdictions have demonstrated that comprehensive regulatory interventions improve contamination management and risk reduction. In the U.S., implementation of the EPA National Primary Drinking Water Regulation (2024), expanded nationwide monitoring, and CERCLA enforcement have strengthened identification of contaminated drinking-water systems and remediation of high-priority sites. Similarly, the EU's precautionary approach under REACH, the proposed Universal PFAS Restriction, and recent wastewater management reforms under the Urban Wastewater Treatment Directive have advanced preventive risk management by limiting future PFAS releases and reducing regrettable substitution [87,88].

Canada and Australia have further demonstrated the value of coordinated national monitoring programmes, class-based regulation, and strengthened contaminated-site assessment in supporting evidence-based decision-making and environmental management [73,75]. Nevertheless, governance effectiveness remains uneven, particularly in developing countries where limited financial resources, analytical capacity, and fragmented legislation constrain implementation. Overall, jurisdictions combining precautionary regulation, comprehensive monitoring, effective enforcement, sustained scientific investment, adaptive management, and international cooperation have achieved the greatest progress in reducing PFAS risks and strengthening long-term environmental governance [88].

7.3. Case Studies and Lessons Learned from PFAS Governance

Effective PFAS governance depends not only on regulation but also on timely implementation, sustained environmental monitoring, institutional capacity, and stakeholder engagement. Experiences across jurisdictions demonstrate that coordinated regulatory action can significantly reduce PFAS exposure, whereas delayed regulation contributes to fragmented governance. In the U.S., widespread contamination associated with AFFFs prompted strengthened regulatory measures, including the EPA National Primary Drinking Water Regulation (2024), expanded monitoring under UCMR 5, and CERCLA enforcement, which have improved contamination identification, public notification, and remediation of priority sites [83].

The EU has adopted one of the world's most precautionary PFAS governance approaches through progressive restrictions under REACH and the proposed Universal PFAS Restriction. By increasingly regulating PFAS as a chemical class rather than individual compounds, the EU seeks to reduce regrettable substitution and promote sustainable chemical management [61]. In contrast, historical compound-specific regulation allowed replacement PFAS, including GenX and other short-chain fluorinated compounds, to enter the market before their environmental behaviour and toxicological effects were fully understood. Evidence of their persistence and mobility has reinforced international support for broader class-based regulation [19,46]. Collectively, these experiences demonstrate that effective PFAS governance requires precautionary and adaptive regulation, comprehensive environmental monitoring, strong enforcement, sustained scientific research, stakeholder engagement, and international collaboration to minimise long-term environmental and human health risks.

7.4. Drinking Water Guidelines

PFAS contamination disproportionately affects communities near military installations, airports, industrial facilities, and waste disposal sites where AFFFs and fluorinated chemicals have historically been used. In the U.S., contamination at military bases has caused prolonged exposure and extensive remediation [89], while similar concerns have been reported among Indigenous communities in Canada and Australia [90]. Environmental justice frameworks advocate equitable protection and meaningful participation in environmental decision-making for all communities [91]. Accordingly, PFAS governance should promote transparent risk communication, stakeholder engagement, equitable access to environmental information, and meaningful community participation to strengthen sustainable environmental governance.

7.5. Industrial Emission Controls

Industrial activities remain major PFAS sources, making emission controls central to risk management [2]. Authorities implement permits, reporting, and restrictions, with industries required to monitor emissions from facilities, discharges, and disposal [16].

Restrictions on PFOS, PFOA, and related compounds under REACH and the Stockholm Convention further reduce industrial production and environmental release [43]. Many industries are additionally being encouraged to transition toward safer alternatives and adopt cleaner production technologies that minimise fluorinated chemical emissions. Nevertheless, industrial substitution with poorly characterised short-chain PFAS compounds continues to present regulatory and environmental challenges.

7.6. Wastewater Treatment Regulations

WWTPs are recognised as important secondary sources of PFAS contamination because conventional treatment processes often fail to completely remove fluorinated compounds from wastewater streams [9]. As a result, many countries have strengthened wastewater monitoring requirements and introduced regulatory guidelines for PFAS discharge into receiving water bodies. Advanced treatment technologies such as granular activated carbon, ion exchange resins, membrane filtration, and advanced oxidation processes have demonstrated improved PFAS removal efficiencies compared with conventional biological treatment systems [92]. Regulatory agencies increasingly recommend or require the adoption of advanced treatment systems in highly contaminated facilities and industrial wastewater treatment operations.

In addition to liquid effluent regulation, growing attention is being directed toward PFAS accumulation in sewage sludge and biosolids. Several countries are evaluating restrictions on land application of contaminated biosolids due to concerns regarding soil contamination, groundwater infiltration, and food chain transfer.

7.7. Product Restrictions and Bans

Product restrictions and phase-outs reduce PFAS exposure, targeting firefighting foams, packaging, textiles, cosmetics, cookware, and consumer goods [6]. PFOS and PFOA are restricted globally under the Stockholm Convention and national laws [93]. Several jurisdictions additionally ban PFAS in packaging, children's products, cosmetics, and foams. Despite increasing restrictions, many replacement PFAS compounds and fluorinated alternatives remain commercially available and insufficiently regulated. The continued introduction of substitute chemicals highlights the importance of adopting broader class-based regulatory approaches rather than regulating individual PFAS compounds separately.

7.8. Polluter-Pays Approaches

Polluter-pays principles have become increasingly important in PFAS risk management and environmental remediation strategies. Under this approach, industries and organisations responsible for PFAS contamination may be held financially liable for environmental cleanup, environmental monitoring programmes, and public health interventions [19].

In the U.S., designation of PFOA and PFOS as hazardous substances under the CERCLA strengthens the legal basis for assigning cleanup responsibility to polluters [56]. Similar liability-based environmental protection mechanisms are also emerging within European and international regulatory systems.

Polluter-pays approaches are intended to encourage industries to minimise PFAS release, improve waste management practices, and adopt safer alternatives. However, implementation may be challenging because contamination often originates from multiple historical sources and legacy industrial activities.

7.9. Environmental Monitoring Programmes

Environmental monitoring underpins PFAS risk assessment, compliance, and management. Programmes worldwide track the occurrence in water, soils, food, wildlife, and human samples [5]. National and international initiatives identify hotspots, trends, and regulatory effectiveness, using LC-MS/MS and HRMS for routine and non-target screening [36]. Several countries have also initiated biomonitoring programmes to evaluate PFAS exposure within human populations, particularly among vulnerable communities located near contaminated industrial sites and firefighting training facilities [4]. Improved environmental surveillance is essential for supporting evidence-based policy development and strengthening long-term public health protection. Effective PFAS management requires integrated policies combining regulation, industrial accountability, treatment technologies, environmental monitoring, and international cooperation. Figure 6 summarises key responses, including drinking-water regulation, industrial controls, wastewater treatment, product restrictions, polluter-pays mechanisms, and monitoring programmes. Collectively, these measures support contamination control, enforcement, environmental protection, and sustainable governance of PFAS risks.

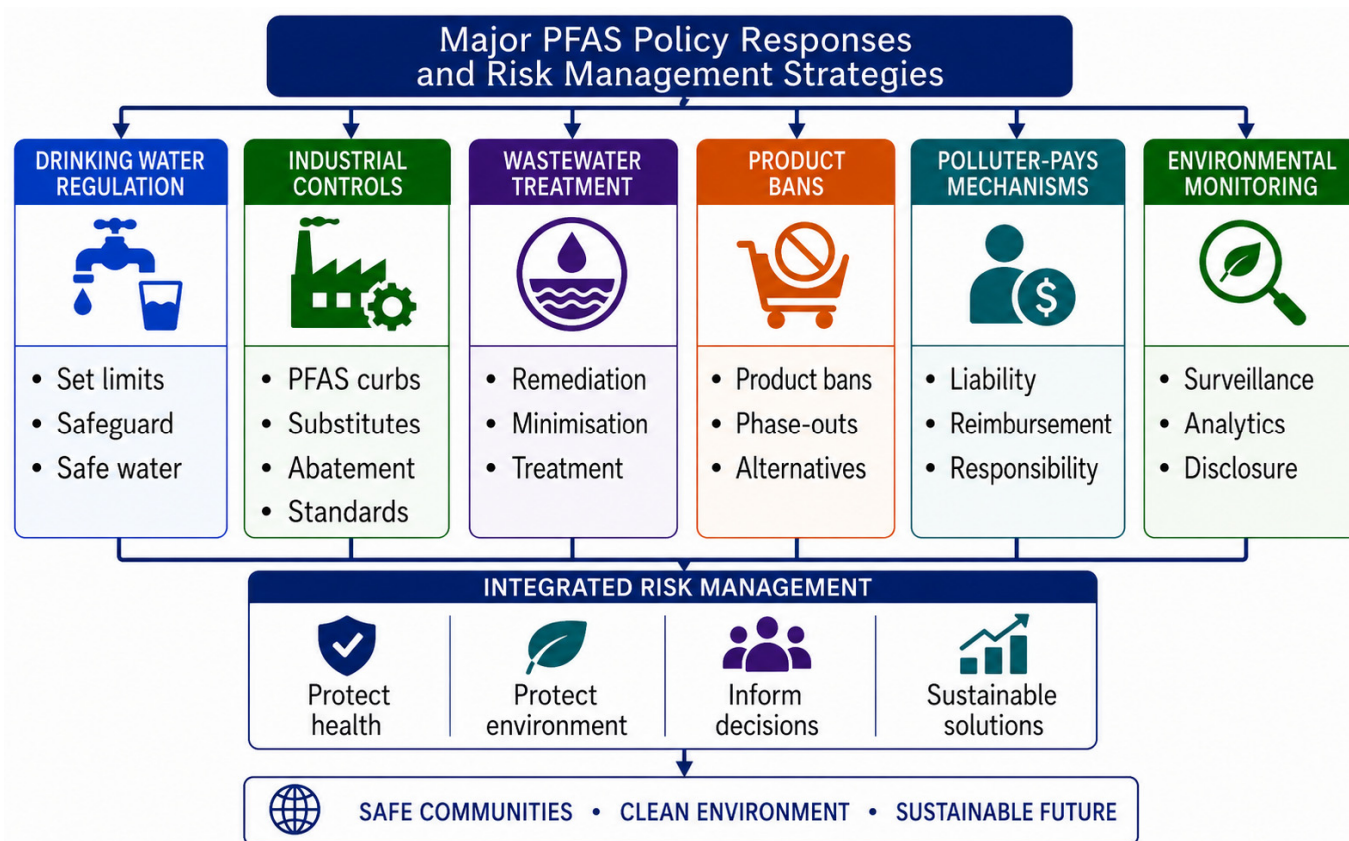


Figure 6. Integrated framework illustrating the major policy responses and risk management strategies used to reduce PFAS contamination, including drinking-water regulation, industrial emission controls, wastewater treatment, product restrictions, polluter-pays mechanisms, environmental monitoring, and their contribution to protecting human health and the environment.

8. PFAS Governance in Practice

Future governance will depend on continued scientific innovation, international cooperation, and adaptive policy development. Growing recognition of PFAS contamination as a complex environmental and public-health challenge has expanded policy discussions beyond conventional regulation toward broader governance approaches. PFAS governance integrates institutions, stakeholders, scientific evidence, environmental monitoring systems, and decision-making processes across the PFAS life

cycle. Effective governance requires coordinated action and emphasises collaboration, transparency, stakeholder engagement, adaptive decision-making, and long-term environmental stewardship [19,43].

Flexible governance frameworks have become increasingly important for sustainable environmental management because scientific knowledge, analytical technologies, and regulatory priorities continue to evolve rapidly. Flexible governance frameworks capable of incorporating emerging scientific evidence are essential for improving long-term environmental resilience and ensuring sustainable management of PFAS contamination.

8.1. Stakeholders in PFAS Governance

PFAS governance involves a diverse network of stakeholders whose actions collectively influence environmental protection and risk management outcomes. Governments play a central role by establishing legislative frameworks, setting environmental quality standards, developing national action plans, and allocating resources for monitoring and remediation activities [94]. Regulatory agencies such as the U.S. EPA, the ECHA, and national environmental authorities are responsible for implementing regulations, conducting risk assessments, and enforcing compliance requirements [62,95].

Industry stakeholders influence PFAS releases through production, formulation, and waste practices, with growing emphasis on safer alternatives, transparency, and stewardship [43]. Scientists provide evidence on occurrence, fate, toxicology, exposure, and remediation, informing policy and regulation [96]. Water utilities play critical roles in monitoring, treatment upgrades, communication, and compliance, though they face technical and financial challenges [14]. Civil society and communities contribute via advocacy, awareness, citizen science, and accountability. Collectively, these actors form an interconnected governance network essential for effective PFAS management.

8.2. Environmental Justice and PFAS Exposure

Environmental justice has emerged as an increasingly important dimension of PFAS governance because contamination often disproportionately affects specific communities and vulnerable populations. Numerous studies have identified elevated PFAS exposure among communities located near airports, military installations, industrial manufacturing facilities, wastewater treatment plants, and landfill sites where PFAS-containing materials have historically been used or released [4,22].

Evidence from several countries shows that PFAS contamination disproportionately affects communities near military installations, airports, industrial facilities, and waste disposal sites where AFFFs and fluorinated chemicals have historically been used. In the U.S., contamination at military bases has resulted in prolonged exposure and extensive remediation programmes [89], while similar concerns have been reported among Indigenous communities in Canada and Australia, highlighting environmental justice challenges [90]. Environmental justice frameworks advocate equitable protection from environmental hazards and meaningful participation in environmental decision-making for all communities [91]. Accordingly, PFAS governance should promote transparent risk communication, stakeholder engagement, community participation in monitoring, equitable access to environmental information, and meaningful consultation with Indigenous Peoples to strengthen public trust, regulatory legitimacy, and sustainable environmental governance.

Communities near military bases and airports face PFAS contamination from historical AFFF use, impacting groundwater and drinking water [20]. Populations near fluorochemical facilities also experience elevated exposure via water, air, and releases [22]. Socioeconomically disadvantaged groups, Indigenous communities, and rural

populations encounter added risks due to limited resources, isolation, and weak monitoring [43]. Equitable governance requires contamination control, transparent communication, stakeholder participation, and inclusion of affected communities in decision-making. Integrating environmental justice principles into PFAS governance therefore not only improves protection of vulnerable populations but also strengthens the transparency, legitimacy, and long-term effectiveness of environmental decision-making, thereby supporting more inclusive and sustainable environmental management. Recognition of these disproportionate impacts has contributed significantly to the broader framing of PFAS contamination as an environmental justice issue, further increasing political attention and accelerating regulatory responses in many jurisdictions.

8.3. Public Perception and Risk Communication

Public confidence in PFAS governance depends on timely, transparent, and scientifically credible communication regarding environmental contamination and associated health risks. Communities affected by PFAS contamination frequently express concerns regarding drinking-water safety, long-term health effects, property values, and the adequacy of government responses. Effective risk communication therefore requires early stakeholder engagement, transparent reporting of monitoring results, acknowledgement of scientific uncertainties, and meaningful opportunities for community participation in environmental decision-making. Community-based monitoring programmes, accessible public information platforms, and regular dialogue between regulatory authorities, researchers, and affected communities have proven effective in improving public trust and supporting informed risk management [97].

8.4. Adaptive Governance

PFAS governance faces challenges from evolving science and over 10,000 compounds, with limited toxicological data for most [19]. As new PFAS enter markets, systems must adapt to emerging risks. Adaptive governance offers flexibility, integrating environmental monitoring, iterative risk assessment, policy review, and stakeholder engagement [98]. Recent initiatives, including EU proposals for class-based restrictions under REACH, reflect growing efforts to regulate PFAS collectively, ensuring proactive protection and sustainable management [61].

The precautionary principle represents another important element of adaptive governance. Under this principle, preventive action may be justified even when scientific uncertainty remains regarding the full extent of environmental or health risks [85]. Given the persistence, mobility, and potential toxicity of many PFAS compounds, precautionary approaches have become increasingly influential in environmental decision-making and chemical management policies worldwide. Adaptive governance, therefore, enables regulators to balance scientific uncertainty with the need for timely environmental protection and risk reduction.

8.5. Challenges in Global Governance

Effective PFAS management requires integrated stewardship combining environmental monitoring, transparent reporting, remediation, and adaptive governance. Monitoring supports evidence-based decision-making and stakeholder engagement [83], while remediation technologies remain essential despite challenges associated with persistent contamination [92]. Addressing these challenges will require greater regulatory harmonisation, enhanced monitoring capacity, improved access to analytical technologies, increased investment in environmental surveillance, and strengthened international collaboration through frameworks such as the Stockholm Convention, OECD initiatives, and emerging global chemicals and plastics governance mechanisms.

Such efforts are essential for achieving effective long-term PFAS governance and reducing environmental and public health risks worldwide.

8.6. Governance Challenges in Emerging Economies

While substantial progress has been made in PFAS regulation and management in North America, Europe, and parts of the Asia-Pacific region, many emerging economies continue to face significant governance challenges that limit their ability to effectively identify, monitor, regulate, and remediate PFAS contamination. These challenges are often linked to constraints in analytical capacity, monitoring infrastructure, regulatory development, financial resources, and technical expertise, resulting in substantial knowledge gaps regarding PFAS occurrence, exposure pathways, and environmental risks [19,43].

8.6.1. Analytical Capacity

One of the most significant barriers to effective PFAS governance in emerging economies is limited analytical capacity. The detection and quantification of PFAS typically require advanced instrumentation such as LC-MS/MS, HRMS, and specialised sample-preparation techniques that are often costly to acquire, operate, and maintain [5]. Consequently, many countries lack sufficient laboratory infrastructure to conduct routine PFAS monitoring, resulting in fragmented datasets and limited understanding of contamination sources and environmental distribution. These analytical limitations can delay risk assessment, hinder evidence-based policymaking, and constrain regulatory development.

8.6.2. Monitoring Infrastructure

Effective PFAS governance relies on robust environmental monitoring systems capable of identifying contamination hotspots, tracking environmental trends, and evaluating the effectiveness of management interventions. However, monitoring infrastructure remains underdeveloped in many emerging economies. Routine surveillance programmes for drinking water, groundwater, wastewater, surface waters, sediments, and biota are frequently absent or limited in geographic coverage due to financial and logistical constraints [78]. As a result, PFAS contamination may remain undetected for extended periods, increasing the potential for environmental persistence and human exposure. Strengthening monitoring infrastructure is therefore critical for improving environmental surveillance, supporting risk assessment, and informing regulatory decision-making.

8.6.3. Regulatory Gaps

Many emerging economies have yet to establish comprehensive PFAS-specific regulations or environmental quality standards. Existing chemical management frameworks often focus on legacy pollutants and may not adequately address the complexity, diversity, and persistence of PFAS compounds [10]. In some jurisdictions, regulatory responses remain reactive rather than preventive, with action occurring only after contamination has been identified. Furthermore, inconsistencies in international regulatory approaches can create challenges for countries seeking to develop harmonised governance frameworks. Addressing these regulatory gaps will require the incorporation of emerging scientific evidence, adoption of precautionary approaches where appropriate, and increased alignment with international best practices.

8.6.4. Resource Limitations

Financial and institutional resource constraints represent another major challenge. Establishing comprehensive PFAS monitoring programmes, upgrading laboratory facilities, implementing remediation technologies, and supporting regulatory enforcement require substantial long-term investment. For many developing countries, competing environmental and public-health priorities may limit the allocation of resources to emerging contaminants such as PFAS [78]. These constraints can affect all stages of governance, from environmental monitoring and data generation to risk communication, remediation, and policy implementation. Consequently, international cooperation, technical assistance, and capacity-building initiatives will be essential for supporting effective PFAS management in resource-constrained settings.

8.6.5. Skills Shortages and Capacity Building

A shortage of trained personnel limits PFAS governance in emerging economies, with expertise concentrated in a few institutions, hindering monitoring and management [67]. Capacity-building through training, collaborations, technology transfer, and knowledge-sharing is critical. Investment in human capital will strengthen technical expertise, enabling effective responses and sustainable participation in global chemical pollution governance.

Overall, addressing governance challenges in emerging economies will require coordinated investment in analytical infrastructure, monitoring networks, regulatory development, technical training, and international collaboration. Strengthening these foundational capacities will improve environmental surveillance, support evidence-based policymaking, and promote more equitable and effective PFAS governance worldwide.

9. Environmental Risk Management Frameworks for PFAS

The persistent, mobile, and bioaccumulative nature of many PFAS necessitates comprehensive environmental risk management frameworks that extend beyond contamination detection and regulatory compliance. Effective risk management requires systematic identification of contamination sources, assessment of exposure pathways, evaluation of potential hazards, implementation of risk-reduction measures, and long-term stewardship activities that support environmental protection and public health. As scientific understanding of PFAS continues to evolve, risk management approaches are increasingly adopting life-cycle and adaptive-management perspectives that integrate monitoring, regulation, remediation, and stakeholder engagement [19,46].

Future advances in PFAS governance should be guided by sustainability principles that integrate scientific innovation, green chemistry, sustainable materials management, and international collaboration. Such approaches will facilitate the transition towards safer chemical alternatives, strengthen evidence-based environmental governance, and support the long-term protection of human health and ecosystems.

9.1. Risk Identification

Risk identification represents the first stage of environmental risk management and involves recognising PFAS sources, contamination pathways, and environmental hotspots. PFAS are released into the environment through numerous activities, including fluorochemical manufacturing, metal plating, textile treatment, paper production, semiconductor fabrication, firefighting foam use, landfill disposal, wastewater discharges, and consumer-product degradation [2,4].

Environmental monitoring programmes have identified several recurring PFAS contamination hotspots worldwide. Airports, military installations, and firefighting

training facilities are among the most extensively documented sites due to the historical use of AFFFs [20,22]. Additional hotspots include industrial manufacturing zones, wastewater treatment plants, landfills, and areas receiving biosolid applications [5]. Identifying these contamination sources and pathways is essential for prioritising monitoring efforts, directing remediation resources, and supporting evidence-based regulatory interventions.

9.2. Exposure Assessment

Exposure assessment identifies PFAS pathways for humans and ecosystems. Drinking water is a major route due to mobility and frequent detection in groundwater and surface supplies [14,22]. Food consumption adds risks via fish, livestock, crops, and packaging [49]. Atmospheric exposure occurs through aerosols, dust, and volatile precursors [4].

Occupational exposure is particularly relevant for workers employed in fluorochemical manufacturing, waste management, metal plating operations, firefighting activities, and remediation projects. These groups often experience higher PFAS exposure levels than the general population due to direct contact with PFAS-containing materials and contaminated environments [99]. Comprehensive exposure assessments, therefore, require consideration of multiple environmental media and exposure pathways to accurately characterise potential risks.

9.3. Risk Characterisation

Risk characterisation integrates exposure and toxicological data to assess PFAS health and environmental risks. Compounds have been linked to developmental, immune, endocrine, reproductive, liver, and cancer effects, though understanding remains uneven [4]. Challenges include uncertainty for emerging PFAS and transformation products, with limited data beyond PFOS/PFOA [2]. Mixture effects, cumulative exposures, persistence, and transformation pathways add complexity. Agencies increasingly adopt precautionary, class-based approaches to address gaps while maintaining protective standards [46].

9.4. Risk Reduction

Risk reduction strategies aim to minimise PFAS releases, reduce environmental exposure, and prevent future contamination. Source-control measures are generally regarded as the most effective long-term management approach because they address contamination before environmental release occurs. Such measures include process modifications, improved waste management practices, containment technologies, and restrictions on PFAS use in industrial applications and consumer products [19,43].

Chemical substitution is a key PFAS risk-management strategy, yet concerns about regrettable substitution highlight the need for careful evaluation of alternatives [6]. Regulatory bans and restrictions also reduce risks, with Stockholm Convention initiatives limiting legacy PFAS. The EU and other jurisdictions increasingly consider class-based approaches [43,61], collectively curbing emissions and exposure.

9.5. Long-Term Stewardship

Effective PFAS management requires long-term stewardship that integrates environmental monitoring, transparent reporting, remediation, and adaptive governance. Environmental monitoring provides essential information on contamination trends, remediation effectiveness, exposure reduction, and emerging PFAS, while transparent reporting enhances accountability, stakeholder engagement, and evidence-based decision-making [83]. Remediation technologies, including activated carbon, ion

exchange, membrane filtration, advanced oxidation, and emerging destruction methods, remain critical despite ongoing challenges associated with widespread contamination and continued PFAS releases [92]. Figure 7 presents an integrated PFAS governance framework linking contamination sources, environmental monitoring, exposure assessment, risk characterisation, policy development, regulation, remediation, and stewardship. Collectively, these interconnected components strengthen adaptive governance, pollution prevention, regulatory decision-making, and the long-term protection of human health and the environment.

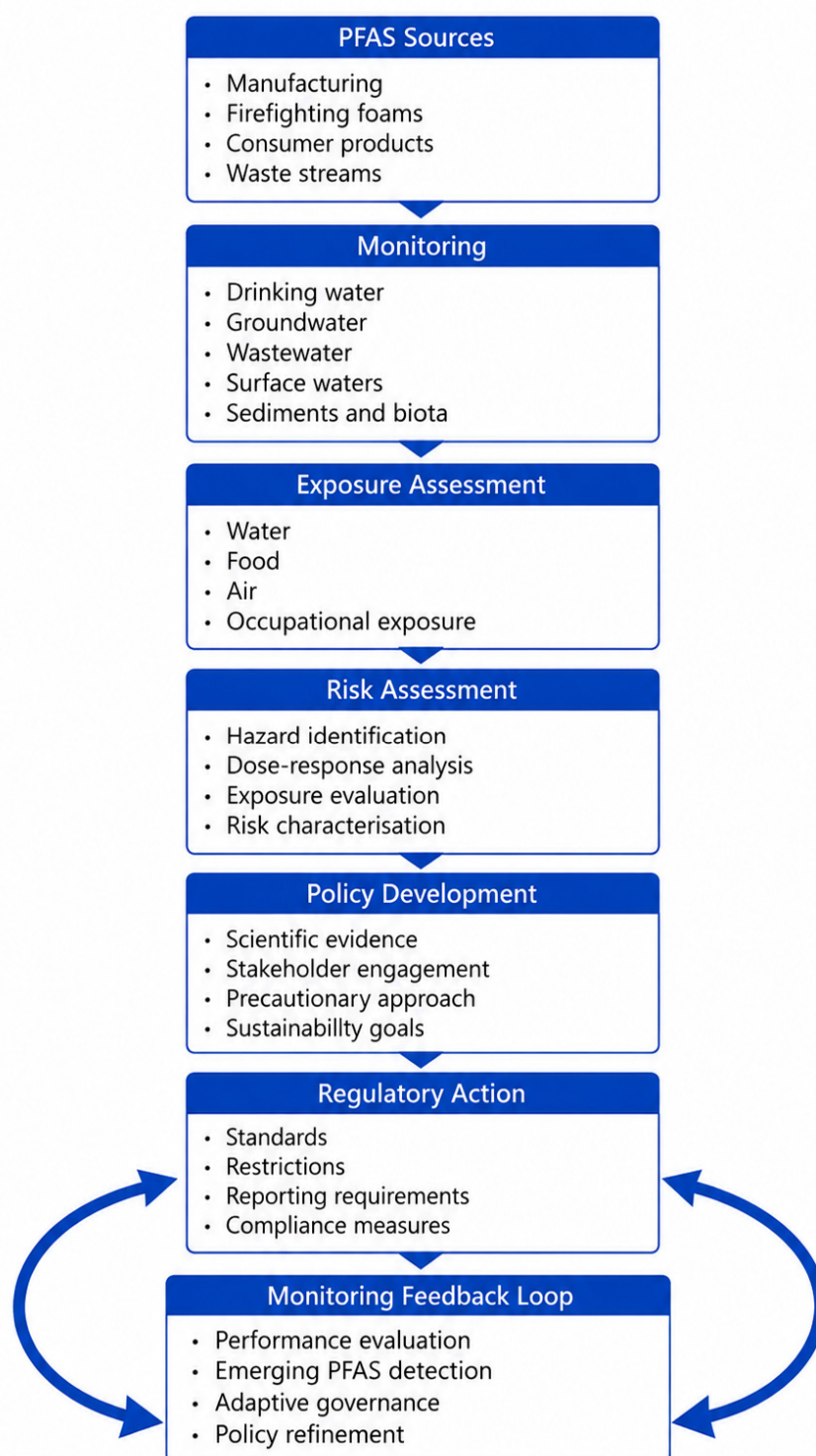


Figure 7. Integrated PFAS governance framework linking contamination sources, environmental monitoring, exposure assessment, risk assessment, policy development, regulatory action, and adaptive feedback mechanisms that collectively support evidence-based decision-making, remediation, and sustainable environmental management.

9.6. Integrating Environmental Justice into Future PFAS Governance

Building upon the recognition that PFAS contamination disproportionately affects vulnerable communities, future governance frameworks should explicitly integrate environmental justice principles into regulatory decision-making, exposure assessment, remediation prioritisation, and community engagement. Incorporating equity considerations into PFAS risk management will help ensure that the benefits of environmental protection are shared fairly while reducing disproportionate exposure among historically underserved populations.

Integrating environmental justice into PFAS governance has become increasingly important because the burdens of contamination are often distributed unevenly across society. While PFAS contamination represents a global environmental challenge, certain populations experience disproportionately higher exposure risks due to their geographic location, socioeconomic status, occupation, or limited access to environmental resources and decision-making processes. Consequently, effective PFAS management requires not only scientific and regulatory solutions but also governance approaches that promote equity, transparency, and the fair distribution of environmental benefits and burdens [4].

9.6.1. Contamination near Military Installations

Military bases and firefighting training facilities have emerged as some of the most significant PFAS contamination hotspots worldwide due to the historical use of AFFFs for fire suppression and training exercises. These activities have resulted in extensive contamination of soils, groundwater, surface waters, and drinking-water supplies in surrounding communities [20,22]. In many cases, contamination has persisted for decades because of the exceptional environmental persistence and mobility of PFAS compounds.

Communities near military installations face elevated PFAS exposure through contaminated water and media, with studies in North America, Europe, and Australia showing concentrations above guidelines [22]. Addressing legacies requires monitoring, transparent communication, remediation, and community engagement for equitable protection.

9.6.2. Indigenous Communities

Indigenous communities face unique PFAS vulnerabilities due to cultural, economic, and subsistence ties to ecosystems. Reliance on fish, wildlife, and natural resources increases exposure through traditional diets [4]. Many communities are located in remote regions with limited monitoring and oversight, reducing opportunities for early detection and intervention, and heightening contamination risks.

Environmental justice frameworks emphasise integrating Indigenous knowledge, cultural values, and participation into decision-making. Meaningful engagement strengthens monitoring, improves risk communication, and supports culturally appropriate PFAS management strategies addressing environmental and social dimensions of contamination [78].

9.6.3. Low-Income Communities and Socioeconomic Inequalities

Socioeconomic factors shape PFAS vulnerability, with low-income communities disproportionately exposed near industrial sites, landfills, and wastewater plants. Limited financial resources restrict access to safe water, treatment technologies, healthcare, and

legal support, constraining responses to contamination concerns and amplifying environmental burdens. Resource-constrained communities face barriers to environmental decision-making, limiting their influence on policy and remediation. These inequalities exacerbate social and health disparities. Equitable access to information, monitoring, and participation is critical for responsible PFAS governance and justice-oriented regulation.

9.6.4. Disproportionate Exposure and Environmental Equity

PFAS exposure is uneven, shaped by land use, industry, infrastructure, and socioeconomic inequalities [22]. Communities near manufacturing, airports, military sites, and waste facilities face higher contamination. Addressing disproportionate risks requires integrating environmental justice into assessment, monitoring, remediation, and regulation. Prioritising vulnerable groups, transparent risk communication, equitable remediation access, and policy equity support sustainable governance, ensuring no community bears unfair PFAS burdens.

Ultimately, environmental justice provides an important lens through which PFAS governance can be evaluated and strengthened. By recognising and addressing disparities in exposure, vulnerability, and access to environmental resources, policymakers and regulators can develop more inclusive and equitable strategies to manage PFAS contamination and protect both human health and environmental quality.

10. Challenges and Limitations in PFAS Regulation

Despite growing global attention, PFAS regulation faces scientific and regulatory challenges. These challenges not only hinder effective environmental governance but also impede progress towards sustainable development by compromising water security, ecosystem integrity, sustainable resource management, and public health protection. Complex chemistry, widespread occurrence, and evolving toxicology hinder harmonised frameworks [2]. A major issue is the lack of unified international standards, with countries applying varying limits, guidelines, monitoring, and risk assessments [19]. These inconsistencies complicate governance, compliance, and contamination management, creating difficulties for multinational industries and cross-border protection, while limiting international cooperation required for sustainable environmental management and the achievement of the United Nations SDGs. Strengthening internationally harmonised regulatory frameworks is therefore essential for promoting sustainable chemical management and reducing transboundary environmental pollution.

Thousands of structurally diverse PFAS remain in use, yet regulation continues to focus mainly on PFOS and PFOA, leaving many compounds insufficiently characterised [1]. Compound-specific regulation has encouraged replacement PFAS such as GenX, which exhibit comparable persistence, mobility, and potential risks [28]. Limited toxicological data [4], costly remediation technologies [92], and analytical constraints associated with ultra-trace detection, specialised instrumentation, and validated methods further hinder effective governance [34]. Replacement PFAS, including short-chain fluorinated compounds, also present continuing environmental and health concerns because of their persistence and mobility [6]. Figure 8 summarises the principal scientific, technical, and regulatory challenges affecting PFAS governance. Addressing these challenges requires harmonised international standards, expanded toxicological research, class-based regulation, improved analytical capacity, and stronger international cooperation to support sustainable environmental management and long-term protection of human health and ecosystems.

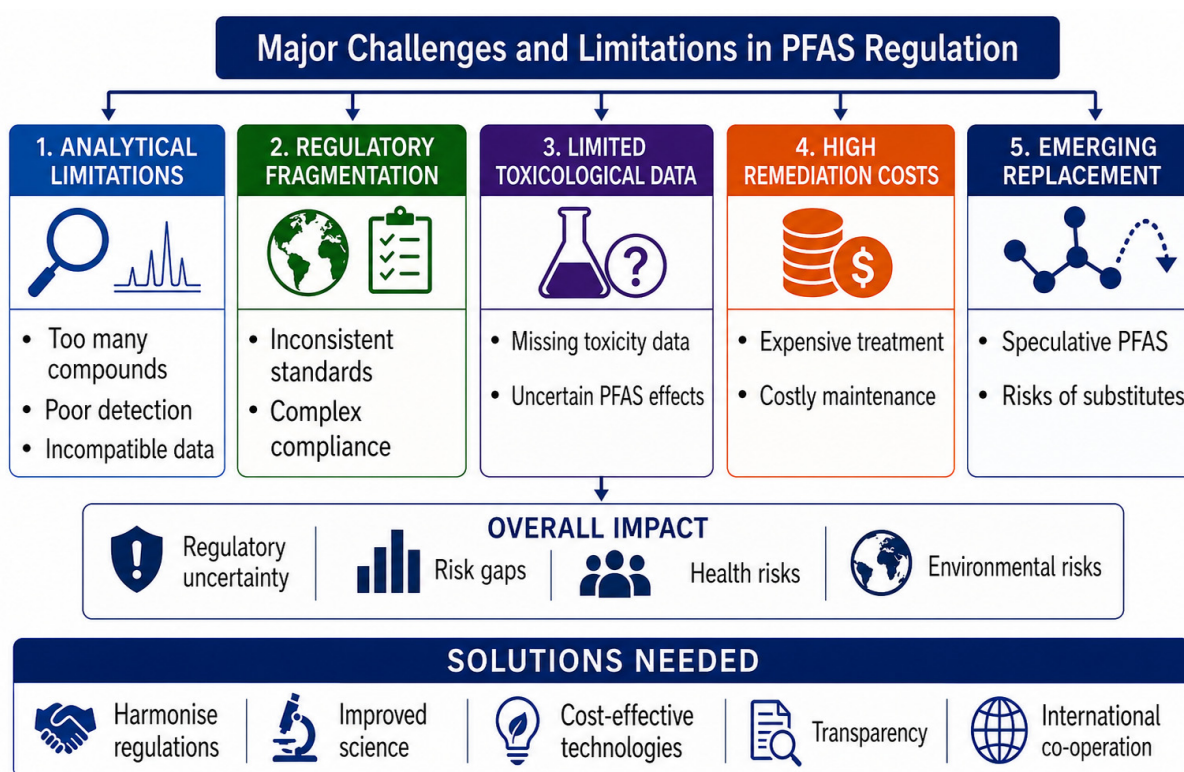


Figure 8. Conceptual overview of the major scientific, technical, and regulatory challenges limiting effective per- and polyfluoroalkyl substances (PFAS) governance, including analytical limitations, regulatory fragmentation, insufficient toxicological data, high remediation costs, and uncertainties associated with emerging PFAS replacement compounds.

10.1. Drivers of Regulatory Fragmentation

Despite growing international recognition of PFAS as contaminants of emerging concern, regulatory fragmentation remains a major barrier to effective global governance because scientific, institutional, economic, and political factors continue to shape national regulatory responses differently. Jurisdictions vary in regulatory philosophy, with some adopting precautionary hazard-based approaches and others relying on compound-specific risk assessment. Differences in analytical capacity, institutional resources, financial investment, and the rapid emergence of new PFAS further contribute to uneven regulatory implementation and hinder international harmonisation despite increasing scientific consensus regarding PFAS risks [52,86]. Political and economic considerations also influence governance, as broad PFAS restrictions raise concerns for industries where fluorinated chemicals perform essential functions and technically feasible alternatives remain under development [11]. Differences in industrial priorities, trade competitiveness, and regulatory costs may therefore delay harmonisation. Strengthening PFAS governance will require transparent stakeholder engagement, evidence-based decision-making, sustainable innovation, and enhanced international cooperation to support regulatory consistency while facilitating the transition towards safer chemical alternatives.

10.2. Managing Scientific Uncertainty in PFAS Governance

Scientific uncertainty remains an inherent challenge in PFAS governance because thousands of PFAS compounds have yet to be fully characterised with respect to their environmental behaviour, exposure pathways, and toxicological effects. Rather than delaying regulatory action until complete evidence becomes available, adaptive

governance provides a practical framework for decision-making under uncertainty. Adaptive governance combines precautionary regulatory measures with continuous environmental monitoring, periodic reassessment of scientific evidence, and progressive refinement of regulatory standards as new knowledge emerges [52]. This approach enables policymakers to manage potential risks proactively while maintaining sufficient flexibility to incorporate advances in analytical chemistry, toxicology, and environmental monitoring. Consequently, scientific uncertainty should be regarded not as a barrier to regulation but as a justification for iterative, evidence-informed governance that strengthens environmental protection over time.

11. Future Perspectives and Recommendations

Growing global concern over PFAS contamination highlights the need for coordinated, sustainable regulatory and environmental management strategies to protect water resources, ecosystems, biodiversity, and human health. Although substantial progress has been achieved in PFAS monitoring and regulation, important scientific, technological, and policy challenges remain. Future efforts should strengthen international cooperation, analytical capabilities, safer chemical alternatives, and sustainability-based governance. Recent initiatives, including the U.S. EPA National Primary Drinking Water Regulation (2024) [71], the EU's proposed Universal PFAS Restriction under REACH, OECD harmonisation of PFAS terminology and analytical methods, the Stockholm Convention's expanded PFAS listings, Canada's proposed class-based Risk Management Approach, and Australia's updated National Environmental Management Plan, demonstrate increasing convergence towards precautionary, science-based governance. These developments promote class-based regulation, enhanced environmental monitoring, and international collaboration. Scientific advisory organisations further support evidence-based governance through health-based guideline values, toxicological assessments, and harmonised analytical approaches, including contributions from EFSA, ATSDR [99], and the OECD to strengthen global PFAS management.

Unified global regulatory frameworks are essential for effective PFAS management because current approaches remain fragmented, resulting in inconsistent standards, restrictions, and monitoring programmes [19]. Greater international harmonisation, supported by agreements such as the Stockholm Convention, should promote class-based regulation to address thousands of toxicologically uncharacterised PFAS and prevent regrettable substitution with structurally similar alternatives [1]. Such frameworks strengthen sustainable chemical management, regulatory consistency, international cooperation, and progress towards the United Nations SDGs. Improved monitoring is equally critical, with advances in HRMS, non-target screening, biosensors, and real-time monitoring enhancing PFAS detection and environmental surveillance across water, soils, sediments, food, wildlife, and human biological samples [36]. Developing safer non-fluorinated alternatives further supports sustainable product design, pollution prevention, and circular economy objectives by reducing persistence, toxicity, and bioaccumulation [6]. Effective PFAS governance should also incorporate product stewardship, supply-chain transparency, safer chemical substitution, and extended producer responsibility to minimise environmental releases throughout product life cycles and reduce future contamination.

Advanced remediation technologies, including plasma treatment, electrochemical oxidation, photocatalysis, supercritical water oxidation, nanotechnology, and enhanced adsorption, show considerable potential for PFAS removal but require further optimisation for cost-effective, large-scale implementation [92]. Transparent risk communication, stakeholder engagement, and community participation are equally

important for strengthening public trust, environmental justice, and sustainable governance [100]. Although granular activated carbon and ion-exchange resins remain effective for many long-chain PFAS, their performance is limited for short-chain compounds and requires environmentally responsible media management [101]. Advanced destructive technologies offer promising PFAS mineralisation but remain constrained by high energy demand, operational costs, scalability, and transformation-product toxicity [102]. Strengthened wastewater policies, improved treatment technologies, sustainable biosolids management, and expanded environmental monitoring are therefore essential to reduce PFAS releases [9]. Future research should prioritise emerging PFAS, mixture toxicity, cumulative exposure, One Health approaches, climate change interactions, and sustainable remediation to support evidence-based environmental management [5].

PFAS governance is increasingly challenged by real-world exposure to complex PFAS mixtures, which are inadequately addressed by traditional compound-specific risk assessment. Growing recognition of mixture toxicity supports class-based regulation and cumulative risk assessment frameworks that better reflect environmental exposure scenarios. Emerging PFAS, including short-chain compounds, GenX, and ADONA, present additional regulatory challenges because of limited toxicological data despite increasing evidence of their persistence and potential health risks. Consequently, future governance should adopt precautionary, class-based approaches that proactively regulate emerging PFAS before widespread environmental contamination occurs. Effective PFAS management also requires integrated multidisciplinary strategies combining scientific innovation, regulatory harmonisation, environmental accountability, advanced remediation technologies, sustainable chemical design, and international cooperation. Figure 9 presents an adaptive governance framework linking regulatory systems, environmental monitoring, technological innovation, stakeholder engagement, and policy feedback into a unified model. Collectively, these strategies strengthen evidence-based decision-making, sustainable environmental management, ecosystem resilience, and long-term protection of human health while advancing the United Nations Sustainable Development Goals.



Figure 9. Conceptual framework for adaptive PFAS governance and sustainable environmental management. The framework integrates global regulation, environmental monitoring, green chemistry, remediation technologies, wastewater management, environmental surveillance, policy development, regulatory implementation, institutional coordination, and adaptive governance within a continuous feedback system to support evidence-based decision-making and long-term protection of human health and the environment.

12. Conclusions

This review provides a comprehensive synthesis of current knowledge on PFAS governance by integrating recent advances in regulatory frameworks, environmental monitoring technologies, risk assessment methodologies, and sustainable environmental management. Unlike previous reviews that have primarily focused on individual aspects of PFAS regulation or analytical monitoring, this review presents an integrated evaluation of governance effectiveness across major international jurisdictions and demonstrates how regulatory, scientific, and technological developments collectively influence long-term PFAS management.

A key finding of this review is that effective PFAS governance extends beyond the establishment of regulatory limits. Jurisdictions that combine harmonised legislation, comprehensive monitoring programmes, robust enforcement mechanisms, institutional capacity, and stakeholder collaboration have generally achieved greater success in reducing environmental contamination and protecting public health. Conversely, fragmented regulatory systems, inconsistent monitoring practices, limited toxicological data, and inadequate analytical capacity remain significant barriers to effective PFAS management in many regions.

The review further demonstrates that future governance should progressively transition from compound-specific regulation towards scientifically supported class-based management, complemented by adaptive governance, internationally harmonised monitoring frameworks, advanced analytical technologies, and sustainable chemical innovation. Strengthening international collaboration, improving data sharing,

expanding monitoring of emerging PFAS, and integrating One Health and circular economy principles will be essential for addressing future environmental challenges associated with these persistent contaminants.

Overall, the evidence synthesised in this review indicates that effective PFAS governance requires an integrated, adaptive, and evidence-based framework linking environmental monitoring, risk assessment, regulatory policy, scientific innovation, stakeholder engagement, and sustainability objectives into a coherent strategy for long-term environmental management. The review further highlights the growing importance of class-based regulation, harmonised international governance, advanced analytical and monitoring technologies, and collaborative decision-making in addressing the complex challenges posed by PFAS contamination. By critically synthesising recent scientific evidence, regulatory developments, and governance strategies within a unified conceptual framework, this review provides practical guidance for policymakers, environmental regulators, researchers, industry, and other stakeholders while identifying priority areas for future research and policy development.

Collectively, these insights contribute to strengthening global PFAS governance and support progress towards the United Nations Sustainable Development Goals through the long-term protection of human health, environmental quality, and ecosystem resilience. Ultimately, safeguarding future generations from PFAS contamination will depend not only on scientific innovation but also on coordinated global governance, sustained political commitment, and the collective commitment to more sustainable approaches to chemical production, environmental stewardship, and resource management.

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Abbreviations

AFFF	Aqueous Film-Forming Foam
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
ECHA	European Chemicals Agency
EFSA	European Food Safety Authority
EPA	Environmental Protection Agency
EU	European Union
FDA	Food and Drug Administration
GC-MS	Gas Chromatography-Mass Spectrometry
GenX	Hexafluoropropylene oxide dimer acid (HFPO-DA)-based fluoropolymer processing aid
HPLC	High-Performance Liquid Chromatography
HRMS	High-Resolution Mass Spectrometry
INC	Intergovernmental Negotiating Committee
LC-MS/MS	Liquid Chromatography-Tandem Mass Spectrometry
MCLs	Maximum Contaminant Levels
OECD	Organisation for Economic Co-operation and Development
PFAAs	Perfluoroalkyl Acids
PFAS	Per- and Polyfluoroalkyl Substances
PFCAs	Perfluoroalkyl Carboxylic Acids
PFOA	Perfluorooctanoic Acid
PFOS	Perfluorooctane Sulphonate
POPs	Persistent Organic Pollutants
PRISMA	Systematic Reviews and Meta-Analyses
QA	Quality assurance
QC	Quality control
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SAICM	Strategic Approach to International Chemicals Management
SDG	Sustainable Development Goal
TSCA	Toxic Substances Control Act
UNEP	United Nations Environment Programme
U.S.	United States
WWTP	Wastewater Treatment Plant

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