Journal of Environment and Earth Science
ISSN 2224-3216 (Paper) ISSN 2225-0948 (Online)
Vol.13, No.10, 2023

Environmental Remediation of Perfluoroalkyl Substances: Current and Emerging Strategies

Efe Jeffery Isukuru [1*] Oghenekohwiroro Edjere [1] Erere Onojeghuo [1] Yemi Hammed Onibiyo [2]
Adekunle Fiyin Ademikanra [3] Dolapo Elizabeth Aluko [4] David Olawale Ipadeola [4]
Azeemat Olanrewaju Olayiwola [5] Birma Johuel Godwin [6] Emmanuel Chimeh Ezeako [7]
1. Department of Environmental Management and Toxicology, College of Science, Federal University of Petroleum Resources, P.M.B. 1221, Effurun, Delta State, Nigeria
2. Department of Pure and Applied Chemistry, Ladoke Akintola University of Technology, P.M.B. 4000, Ogbomoso, Oyo State, Nigeria
3. Department of Biology, San Diego State University, CA., USA.
4. Department of Biochemistry, Ladoke Akintola University of Technology, P.M.B 4000, Ogbomoso, Oyo State, Nigeria
5. Department of Microbiology, Faculty of Science, Federal University, Oye-Ekiti, P.M.B. 373, Km 3 Oye – Afao Road, Ekiti State, Nigeria
6. Department of Environmental Science and Management Technology, Petroleum Training Institute, Effurun, Delta State, Nigeria
7. Department of Biochemistry, University of Nigeria, Nsukka, 410001, Enugu, Nigeria
* E-mail of the corresponding author: Isukuruefejeffery@gmail.com

Abstract

Perfluoroalkyl substances (PFAS) represent a significant challenge to environmental systems due to their extensive presence in everyday consumer products and industrial processes, resulting in the contamination of water and soil sources and consequent negative impact on human health. This review aims to provide a comprehensive overview of the current approaches and their potential for mitigating the environmental impact of these persistent substances. By exploring technological advances in the remediation of PFAS, this review intends to contribute to the understanding appropriate technologies to mitigate the environmental risks associated with PFAS. By focusing on combined treatment strategies, synergistic approaches, advanced tools, and addressing knowledge gaps, more efficient, sustainable, and reliable technologies can be developed for the environmental management of contaminants of interest.

Keywords: Environmental remediation, Perfluoroalkyl substances (PFAS), Emerging strategies, Contaminant management, Sustainable technologies.
DOI: 10.7176/JEES/13-10-04
Publication date: December 31st 2023

1.0 Introduction

Per- and polyfluoroalkyl substances (PFAS) are a group of aliphatic carbon compounds in which hydrogen atoms are replaced by fluorine atoms. Their presence dates to the 1940s, when polytetrafluoroethylene (PTFE) was first introduced as a non-stick coating (Gander, 2022). Over time, these substances have garnered global attention due to their remarkable persistence and their ability to accumulate in organisms' tissues. Anthropogenic activities, ranging from the use of aqueous film-forming foam (AFFF) in firefighting facilities to the application of water and oil-repelling compounds in domestic settings like kitchenware coatings, have contributed to the introduction of PFAS into soil and water systems (Vo et al., 2020; Yao et al., 2022). As PFAS continue to attract global attention due to their persistence and bio-accumulative nature, their introduction into soil and water systems through various anthropogenic activities has become a pressing environmental concern (Bolan et al., 2021a; Halonen et al., 2021)

In industrial settings, PFAS play a vital role in a diverse range of applications due to their unique chemical properties. The production of non-stick coatings like polytetrafluoroethylene (PTFE) for cookware, food packaging, and industrial equipment represents one of the most common industrial uses such as reactor vessels and storage tanks, pump fittings and seals, tubing, etc (Ismaeili et al., 2022). Additionally, PFAS compounds find application in manufacturing semiconductors, textiles, electronics, and firefighting foams (Dasu et al., 2022; Tansel, 2022). These industrial processes significantly contribute to the release of PFAS into the environment during production, usage, and disposal stages. Other industrial activities, such as metal plating, paper production, and oil recovery, have also been identified as notable sources of PFAS contamination (Liu et L., 2022; Glenn et al., 2021; Cai et al., 2022). Effluents generated during these processes can release PFAS compounds into water bodies and soil, leading to environmental contamination. An understanding of industrial processes related to PFAS is essential for developing effective strategies for remediation and minimizing environmental impact.

In contrast to industrial processes, residential sources of PFAS primarily arise from the use of consumer products and household items. PFAS-containing products, including non-stick cookware, water-repellent fabrics, and stain-resistant carpets, are commonly found in households (Emiliano et al., 2022; He et al., 2022). Over time, these products can release PFAS into the indoor environment, contributing to household dust and potentially contaminating nearby soil and water sources. Furthermore, the use of personal care products, cleaning agents, and fire extinguishing foams can introduce PFAS into residential wastewater, with potential implications for sewage treatment plants and groundwater (Comber et al., 2021). It is crucial to differentiate between industrial and residential sources of PFAS contamination to tailor targeted remediation approaches and effectively address environmental challenges in each situation.

In Australia, a study conducted by Nguyen et al., (2022) detected the presence of PFAS in the influent of 76 municipal wastewater treatment plants. These plants served approximately 53% of the population and identified twelve specific PFAS analytes, including six C5-C10 perfluoroalkyl carboxylic acids (PFCAs), four C4-10 perfluoroalkyl sulfonic acids (PFSAs), and two fluorotelomer sulfonates (FTS) - namely, 6:2 and 8:2 FTS. In Florida, Li et al. (2022) reported the ubiquitous presence of PFAS in both tap water ($N = 10$) and surface water samples ($N = 38$). The total concentrations in these samples reached as high as 169 ng L^{-1}, with notably elevated levels (> 60 ng L^{-1}) observed in areas near sources such as military airbases, wastewater facilities, and airports, as well as in polluted rivers or coastal estuaries like Biscayne Bay. Meanwhile, Stefano et al. (2023) found PFAS contamination in groundwater samples collected from Porto Alegre, Brazil. Concentrations in these samples ranged from 22 to 718 ng L^{-1}, with eleven different PFAS species detected, including Perfluorooctanoic Acid (PFOA), Perfluorohexanoic Acid (PFHxA), Perfluoropentanoic Acid (PFPeA), Perfluorobutanoic Acid (PFBA), Perfluorodecanoic Acid (PFDA), Perfluorononanoic Acid (PFNA) and Perfluorooctanesulfonic Acid (PFOS). In Tianjin, China, Ma et al. (2022) assessed PFAS concentrations in various functional areas. The study revealed concentrations ranging from 0.21 ng/g to 5.35 ng/g, with a mean concentration of 1.25 ng/g in the topsoil. Perfluorooctanoic acid (PFOA) was identified as the primary PFAS, and the presence of 6:2 chlorinated polyfluorinated ether sulfonate (6:2 Cl-PFESA) at slightly higher concentrations than PFOS indicated its gradual replacement of legacy PFOS in the region due to emerging use. Moreover, Kurwadkar et al. (2022) reported PFOA and PFOS compound concentrations of 10 ng/L each in the United Kingdom. This global distribution of PFAS contamination underscores the urgent need for effective remediation strategies.

While Nigeria is a developing country, the monitoring and detection of PFAS remain scarce, and only a few studies have been conducted on this issue due to limited analytical capacity in the country. Previous studies have sampled three municipal wastewater treatment plants, two industrial effluent treatment plants, and one hospital wastewater treatment plant in Lagos, Oyo, and Ogun states in Southwest Nigeria. These studies revealed the presence of certain PFAS substances, such as polychlorinated dibenzodioxins (PCDDS), and polychlorinated dibenzofurans (PCDFs), at concentrations ranging from 42-3206.6 ng/kg and 3.2-627.6 ng/kg, respectively (Sindiku et al., 2013; Sindiku et al., 2014). However, the true extent of PFAS pollution in Nigeria and Africa remains largely unknown due to the scarcity of data.

Considering the potential risks associated with PFAS contamination and the lack of comprehensive information, it is crucial to address this issue by implementing effective remediation technologies. The development and application of such technologies are vital to prepare regulatory environmental agencies in Nigeria and other areas of the world for the containment, management, and remediation of pollutants in the area. Therefore, this literature review aims to explore efficient and sustainable treatment mechanisms that can be utilized for the environmental management of contaminants of interest, specifically focusing on PFAS, in Nigeria and in countries were the concentrations of PFAS compounds have been implicated. By investigating technological advances in PFAS remediation, this review intends to contribute to the understanding and implementation of appropriate measures to mitigate the environmental and health risks associated with PFAS contamination in Nigeria and in other countries.

1.1 Origin and historical use of PFAS

Fluorinated surfactants, commercially available since the 1950s, have become indispensable in various industries due to their unique properties, including low aqueous surface tension, foaming abilities, and chemical stability (Eisentein et al., 2017). These surfactants, find application in firefighting foams, coatings, mining, electroplating, and photography (Chirikona et al., 2022) as depicted in Figure 1. Moreover, PFAS play a vital role in the synthesis of diverse products, such as electrical cables, surfactants, carpets, rugs, firefighting materials, pesticides, packaging, and paints (Eisentein et al., 2017; Chirikona et al., 2022).

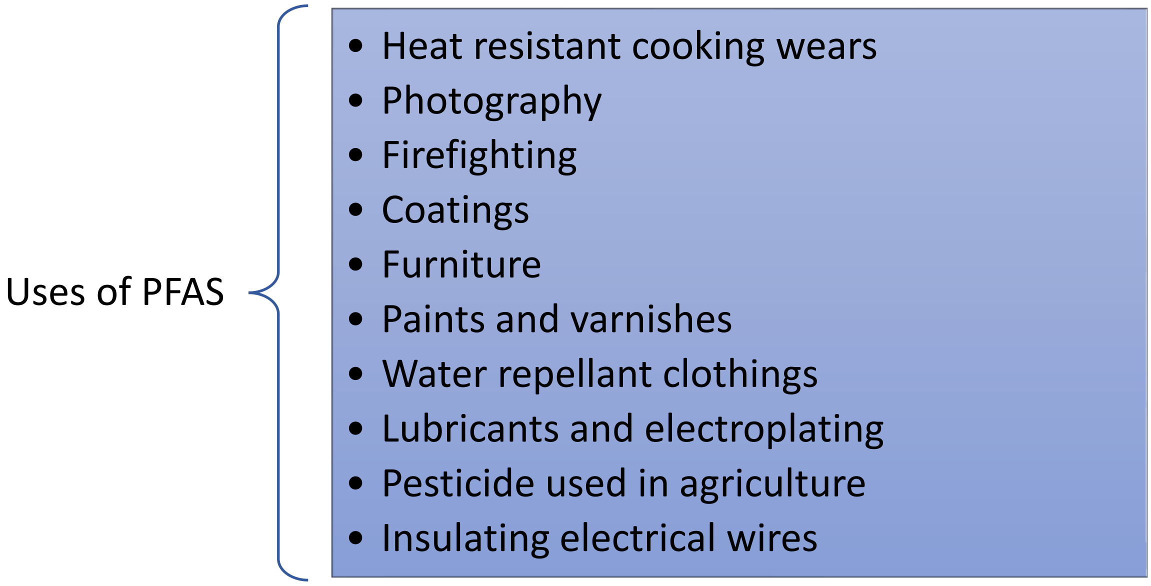

Figure 1: Some identifiable uses of PFAS

The exceptional properties of PFAS are attributed to the strength of the carbon-fluorine (C-F) bond, a strength derived from the high electron affinity of fluorine atoms (Hunter, 2010). This unique bond imparts resistance to acids, alkalis, redox reactions, high temperatures, and hydrophobicity (Berhanu et al., 2023). Consequently, PFAS have found applications in diverse industrial sectors, including agro-industries, pharmaceuticals, catalysis, and polymer manufacturing (Hunter, 2010; Salvatore et al., 2022).

Diverse functional groups at the terminal carbon atom of PFAS molecules, such as carboxylic in perfluorooctanoic acid (PFOA) and sulfuric in perfluorooctanesulfonate (PFOS), influence their chemical behaviour and nomenclature (Wickam, 2020). The manufacturing process involves the fluorination of specific organic compounds within industrial facilities, leading to the production of PFAS derivatives like PFOA and PFOS, which serve as intermediate compounds for shorter-chain PFAS extensively utilized in various industries (Li et al., 2019).

As the demand for PFAS-containing products rises, these substances have become pervasive environmental pollutants, contaminating air, soil, and water. Industrial emissions and the degradation of everyday products contribute to the introduction of PFAS into the environment (Li et al., 2019). Managing the resulting chemical waste is critical to preventing adverse effects on ecosystems and human health.

In various industries, such as firefighting, electroplating, mining, and agriculture, fluorinated surfactants are instrumental. For instance, in agriculture, perfluoroalkyl compounds are used in the synthesis and testing of pesticides, demonstrating advantages in insecticides and pest control (Tudi et al., 2021). Additionally, fluorinated surfactants contribute to the electronic industry by facilitating electron transport in components like semiconductors and transistors (Shimizu et al., 2013; Feng et al., 2019).

While fluorinated surfactants offer economic benefits and diverse uses across industries, concerns about their environmental impact, especially those containing PFAS, have prompted regulatory actions and increased research into safer alternatives (Meegoda et al., 2020; Lohmann et al., 2020). Ongoing efforts focus on developing sustainable alternatives and enhancing waste management practices to mitigate potential risks associated with fluorinated surfactants (Van Der Veen and Kapadia, 2021; Zhang et al., 2023). Balancing economic benefits with environmental sustainability remains a challenge, emphasizing the need for continuous development of safer alternatives and improved waste management practices.

1.2 Types of Perfluoroalkyl Substances PFAS

Perfluoroalkyl substances (PFAS) encompass a wide array of chemical compounds, and since the phasing out of PFOS and PFOA in the early 2000s, various alternative/novel PFAS have been introduced. These novel PFAS include perfluoroalkyl ether sulfonic acid (PFESA), perfluoroalkyl ether carboxylic acids (PFECAs), perfluorobutanesulfonic acid (PFBS), perfluorobutanoic acid (PFBA), perfluoropolyether (PFPEs), polyfluoroalkyl phosphate diesters (diPAPs), 6:2 fluorotelomer sulfonate (FTSA), perfluorinated sulfonamidoacetic acids (FOSAA), 6:2 chlorinated polyfluorinated ether sulfonate (F53B), and new generation (GenX) PFAS, which include hexafluoropropylene oxide (HFPO) dimer acid and its ammonium salt (Glüge et al., 2020; Boisacq et al., 2023). These novel PFAS have been widely adopted as alternatives in various industries to replace PFOS and PFOA.

The replacement of PFOS in electroplating and firefighting foam manufacturing with PFESA, FTSA, PFBS, and F53B, and the replacement of PFOA in the production of high-performance fluoropolymer materials with PFECA and GenX chemicals, has resulted in a variety of PFAS with different chemical structures. These novel PFAS have seen initial expectations that they would be less recalcitrant and break down more easily into less toxic byproducts compared to PFOS and PFOA. However, studies have shown that some of these alternatives, such as PFBS and GenX chemicals, are still toxic, persistent, and mobile in the environment, raising concerns over their environmental and health implications (USEPA, 2018). As a result, some of these novel PFAS, including GenX chemicals, have been listed as Substances of Very High Concern due to their persistent nature, bioaccumulative tendencies, and toxic properties (Gebbink and van Leeuwen, 2020). The occurrence of novel PFAS has been reported in different regions globally, with variations in detection frequency, pollution concentrations, and occurrence locations, mainly due to differences in the phase-out timelines of legacy PFAS between developed and developing regions (Pan et al., 2018).

2.0 Sources and pathways of PFAS contamination in water

Perfluoroalkyl Substances (PFAS) present a formidable challenge to water systems due to their widespread presence in everyday consumer products and industrial processes (Groffen et al., 2018; Groffen et al., 2021; Chirikona et al., 2022). The disposal of PFAS-containing materials from these products into water channels emerges as a major source of contamination (Groffen et al., 2021). PFAS can be transported through various pathways, including surface runoff, leaching from landfills, and discharge from wastewater treatment plants (Ahrens et al., 2011; Masoner et al., 2020). Factors such as solubility, adsorption, and bioaccumulation contribute to their persistence in water systems.

The presence of PFAS in water, encompassing both surface water and groundwater, raises significant concerns for human health (Lyu et al., 2022). The detection of PFAS in drinking water sources and in aquatic organisms and their tissues suggests the potential for biomagnification within the food chain (Lewis et al., 2022). This underscores the need for a comprehensive understanding of the sources and pathways of PFAS contamination in water.

Industries play a pivotal role in the introduction of PFAS into water systems, with the production and utilization of PFAS-based products leading to the release of contaminated wastewater into municipal rivers, lakes, and oceans (Wang et al., 2013; Brunn et al., 2023). In regions with inadequate wastewater treatment systems, such as many African countries, the risk of contamination is exacerbated (Brunn et al., 2023). Conventional wastewater treatment plants are often insufficient to remove PFAS compounds effectively, allowing them to persist in rivers and other bodies of water.

In regions with inefficient wastewater treatment plants, such as Nigeria and other parts of Africa, the discharge of untreated wastewater into nearby rivers and lakes is a common practice (Kayode et al., 2018; Onu et al., 2023). This practice significantly contributes to the persistence of PFAS compounds in wastewater and rivers, posing a significant threat to both aquatic organisms and human health through the consumption of drinking water (Shahsavari et al., 2021). The lack of efficient wastewater treatment in these regions contributes to the persistence of PFAS compounds as they do not readily decompose over time.

Spills of PFAS at various stages, such as primary and secondary production, branding processes, transportation, and agricultural use, have further contributed to changes in PFAS concentrations in surface water, stormwater, atmospheric water (clouds), underground water, mainstream water, and their tributaries in surrounding areas (Gallen et al., 2017). These spills contribute to the dynamic nature of PFAS contamination, and the challenges associated with monitoring and mitigating their impact on water systems.

Due to their solubility, PFAS compounds can readily mix with the aqueous media of the human body, remaining non-biodegradable for extended periods and resulting in gradual bioaccumulation (Pérez et al., 2013; Pizzuro et al., 2019). Particularly, the highly water-soluble compounds such as perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) exhibit stability in water, determined by their anionic forms, which have higher solubility than their neutral forms across a range of environmental pH values (Burns et al., 2008). The concentration of PFAS in the aqueous media of the human body can influence the functioning and structure of body organs.

2.1 Sources and pathways of PFAS contamination in soils and sediments

Sediments are pivotal deposition sites for contaminants, including perfluoroalkyl substances (PFAS) (Beylich, 2011). PFAS infiltrate soil and sediment through various pathways linked to commercial product use and disposal. Durable goods such as rugs, carpets, firefighting foam, packaging materials, and surfactants significantly contribute to PFAS release into the soil (Schedin, 2013). These products act as major contamination sources, releasing suspended particles into the air, base water, underground water, and sediments, eventually settling in soil systems.

Once introduced, PFAS compounds persist in sediment, accumulating over time (Kurwadkar et al., 2022; Pétré et al., 2022; Lenka et al., 2022). Their widespread presence in rivers raises concerns about health and environmental impacts from prolonged exposure, necessitating effective treatment methods for PFAS contamination in both wastewater and drinking water sources.

Understanding PFAS behaviour in sediment systems is critical for comprehending potential risks associated with contamination. Sediment-water exchange processes play a significant role in influencing PFAS movement and concentration in both sediments and water columns.

PFAS exhibit persistent behaviour across soil systems (Campos-Pereira et al., 2022). Their resistance to degradation and biomagnification in the food chain raises concerns for human health and ecosystems. Knowledge of PFAS behaviour in water systems, soils, and sediments is crucial for developing effective remediation strategies.

Understanding PFAS behaviour in soil matrices is vital for assessing mobility, persistence, and leaching potential (Milinovic et al., 2015; Campos-Pereira et al., 2022). Soil composition, including minerals, organic matter, and texture, determines PFAS adsorption and retention. High organic matter, like humus, retains PFAS well due to its adsorptive nature. Soil pH influences PFAS speciation and solubility, affecting leaching or plant uptake. Moisture content governs PFAS mobility in soil, impacting transport and potential migration to groundwater (Sarkar et al., 2021). These factors collectively shape PFAS fate in soil, essential for contamination assessment and remediation planning.

PFAS compounds, with hydrophilic and hydrophobic characteristics, transport from contaminated soil to biotic components of ecosystems, including plants. This occurs through processes like diffusion onto root surfaces, subsequent spreading, and transfer to ecosystem consumers, either directly or indirectly (Abunada et al., 2020). These mechanisms contribute to potential PFAS accumulation throughout the food chain, highlighting the importance of understanding PFAS fate and behaviour in soil and sediment environments.

Leaching of PFAS into groundwater is influenced by soil structure and composition, affecting movement and retention within soil profiles (Nguyen et al., 2020; Qi et al., 2022). Understanding soil properties is essential for predicting PFAS mobility and persistence. Numerous studies emphasize the significant impact of PFAS toxicity on soil quality, structure, functioning, and soil organisms, disrupting nutrient cycling, microbial communities, and overall soil health, with consequences for agricultural sustainability and ecosystem dynamics (Wu et al., 2023; Xu et al., 2023). The concentrations of PFAS around the world showing it is not only found within a particular confine of the earth's surface or environmental matrix is shown in table 1 below.

Table 1: Per- and Polyfluoroalkyl Substances (PFAS) Concentrations in Different Matrices from Around the World

Region/Country	**Concentration range of PFAS**	**Matrix**	**Author**	**Potential Human Health Effect**
United States	13.4 – 17.6 (ng/L)	Water	Wang et al. (2022)	Increased risk of cancer, thyroid disease, and reproductive problems
Canada	0.52-2.3 (ng/L) in Aquatic plant samples, 0.012-87 (ng/L) in water samples, not detected – 0.048 (ng/L) in sediment samples, 92±34 (ng/L) in fish samples	Water, plant samples, Fish, and Sediment	Munoz et al., (2022)	Increased risk of cancer, liver disease, and immune system problems
Mexico	23.5 ± 6.5- 591.1 ± 39 (ng/L)	Wastewater	Rodríguez-Varela et al. (2021)	Increased risk of cardiovascular disease associated with exposure to PFAS in wastewater.
Spain	0.18-1.02 (ng/L)	Fish and Shellfish samples	Domingo et al., (2012)	Increased risk of cancer, developmental delays, and immune system problems
South Korea	0.17-3.03 (ng/L)	Food items	Heo et al. (2014)	Increased risk of cancer, developmental delays, and immune system problems in infants
Australia	10 (ng/L)	Fish	Kannan et al., (2018)	Increased risk of cancer, developmental delays, and immune system problems
Europe (Belgium, Czech Republic, Italy and Norway)	0.01-0.11 (ng/L)	Food commodities	Hlouskova et al., (2013)	Increased risk of cancer, liver disease, and immune system problems

Region/Country	**Concentration range of PFAS**	**Matrix**	**Author**	**Potential Human Health Effect**
China	0.30 – 63.3 (ng/L)	Lake	Li et al., (2024)	Increased risk of cancer, liver disease, and immune system problems
South Africa	0.08–15.51 ng mL^{-1} and 0.42–5.74 ng mL^{-1} in dairy milk and infant formula respectively	Dairy milk and infant formula	Macheka et al., (2021)	Potential developmental risks in infants, Liver and metabolic health concerns, and immune system dysfunction
Vietnam	7.76-14.74 ng/L	Wastewater	Nguyen, (2023)	Immune system effects, liver toxicity, and potential links to certain cancers.
Uganda	5.6-9.1 ng/L, 1.0-2.5 ng/L, 1700-7900 pg/g, 160 pg/g, 380 pg/g in wastewater, sediment, Lake Victoria, soil, Maize, Sugar cane stems respectively.	Wastewater, Sediment from Lake Victoria, Soil, Maize cobs, Sugar cane stems	Dalahmeh et al., (2018)	Health problems associated with long term persistent release of wastewater effluents, Bioaccumulation in plants that might be consumed by humans and animals leading to potential health problems.
Nigeria and Ghana	2.6-405.8 µg/kg	Soil samples	Eze et al., (2023)	Endocrine disruption and developmental effects, Reproductive effects, Liver and immune system disorder
Nigeria	0.05-5.0 ng/g	Soil samples	Ibor et al., (2020)	Immune system disorder and potential bioaccumulation in plants.
Germany	0.75-3530 µg/kg	Soil samples and aquatic organisms	Kotthoff et al., 2020	Bioaccumulation in aquatic organisms with the potential for consumption by humans.
Netherlands	1-6800 ng/L	Surface Water samples	Gebbink et al., 2020	Developmental and reproductive effects, Immune system suppression and increased cancer risk.
New Zealand	0.1 – 13 ng/L	Wastewater samples	Lenka et al., (2022)	Potential exposure through drinking water sources. Bioaccumulation in aquatic organisms
Sweden	50 and 1124 ng/g	Wastewater samples	Fredriksson et al., (2022)	Potential exposure to drinking water sources posing potential health risk to humans. Developmental issues, immune system suppression, and potential liver damage. Aquatic ecosystem impact
Japan	0.01-335.79 (ng/L)	Soil samples	Thepakson et al., (2022)	Exposure through soil ingestion and dust, and potential water contamination sources.

Region/Country	Concentration range of PFAS	Matrix	Author	Potential Human Health Effect
Norway	6.5 ± 1.3 ng/L in surface snow, 2.5 ± 1.7 ng/L in freshwater samples, 2.3 ± 1.1 ng/L in seawater samples, 1.05 ± 0.64 ng/L in lake sediments, and 0.084 ± 0.038 ng/g in marine sediments	Meltwater, Surface snow, Freshwater, Seawater, Lake sediments, and Marine sediments.	Ahrens et al., (2023)	Snow Ingestion and inhalation through snow melt. Bioaccumulation in seafoods. Potential impact in aquatic ecosystems, and possible long-range transport.
South Korea	20.7–98.2 pg/m^3, 17.7–467 ng/L, 0.04–15.0 ng/g, n.d.–12.9 ng/g, and n.d. to 197 ng/g in air, water, sediment, soils and fish samples respectively.	Air, water, sediment, soils and Fish samples	Lee et al., (2020)	Terrestial Ecosystem disruption, Airborne exposure, and potential seafood contamination.
India	0.4-10.2 ng/L	Surface water from the Ganges River	Sharma et al., (2016)	Bioaccumulation in aquatic organisms. Potential contamination of groundwater sources.
Czech Republic	n.d.- 23.9 ng/L	Tap drinking water	Dvorakova et al., 2023	Possible effects on the immune system, liver, kidneys, and endocrine system when ingested with potential susception on pregnant women and children.
Poland	0.00403-614 ng/g	Sediment	Gałęzowska et al., (2021)	Potential disruption in benthic ecosystems. Potential accumulation in sediment-dwelling organisms.
Malaysia	0.31–3693.96 ng/g	Dust samples	Haron et al., (2022)	Possible systemic effects, including liver and kidney damage, immune system suppression and developmental issues in children.
Brazil	5400 pg/g, 979 pg/g, and 1020 pg/L, in soil, plants and coastal water respectively.	Soil, Plants and coastal water	Nascimento et al., (2018)	Potential endocrine disruption,

Take note: n.d. means not detected

3.0 Fate of PFAS in the environment

When Perfluoroalkyl substances (PFAS) are introduced into the environment, they undergo complex fate and transport processes, illustrated in Figure 2 below. These processes involve a range of mechanisms, including direct release during manufacturing, leaching from products, and the degradation of PFAS-containing materials such as carpets and clothing (Wen et al., 2014; McDermett et al., 2022; Pickard et al., 2022). These compounds exhibit remarkable persistence, as highlighted in Figure 2, making them resistant to degradation by sunlight, water, and bacteria.

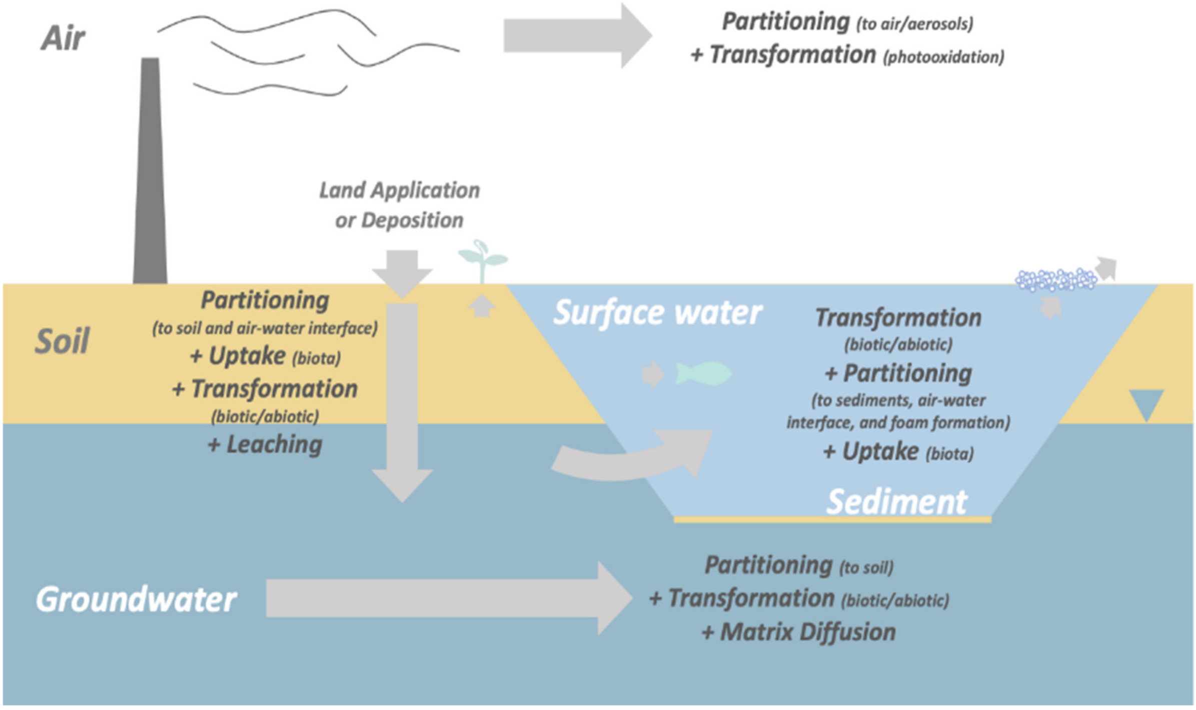

Figure 2: Fate and Transport Processes of PFAS (ITRC, 2022)

As demonstrated in the Figure 2, the journey of PFAS encompasses partitioning into different environmental matrices, including soil and the air-water interface. Here, they may undergo processes of uptake, transformation, and leaching, further contributing to their widespread presence (Ankley et al., 2021; Savoca and Pace, 2021). This persistence and propensity for accumulation in various environmental matrices have led to the phenomenon known as biomagnification, where PFAS accumulate in the tissues of plants and animals (Stahl et al., 2011). These complex processes depicted in Figure 2 underscore the challenges posed by PFAS in the environment and emphasize the importance of understanding their fate and transport dynamics to mitigate their impact effectively (Stahl et al., 2011; Ankley et al., 2021; Savoca and Pace, 2021).

The environmental impact of PFAS encompasses a range of effects on wildlife. Scientific studies have demonstrated that PFAS can disrupt the endocrine system and interfere with the development and reproduction of animals (White et al., 2011; Olufsen and Arukwe., 2015). Additionally, PFAS have been found to affect the immune system, potentially leading to increased susceptibility to diseases (White et al., 2011).

4.0 Health risks of PFAS in the environment

Per- and polyfluoroalkyl substances (PFAS) exhibit high persistence in both the environment and the human body, and they can enter the environment through waste streams or production processes. Certain PFAS have been demonstrated to have detrimental effects on the immune, reproductive, and developmental systems of humans and animals (USEPA, 2022a). Human exposure to PFAS often occurs through inhalation of air containing PFAS, use of products containing perfluoro-chemicals (PFCs), consumption of food contaminated with PFCs, or drinking water contaminated with PFCs from groundwater and surface water sources (Li et al., 2020). Humans can also be at risk of PFAS in soil through direct contact, or these substances may leach into groundwater and surface water bodies. PFAS are considered hazardous air pollutants that contribute to air pollution and have adverse effects on human health (DNR, 2022). Additionally, PFAS can be released into the environment through various sources.

PFAS are persistent pollutants that have slow degradation rates in the environment. Previous studies have indicated that exposure to different PFAS in the environment may have negative impacts on both human and animal health (USEPA, 2022a).

4.1 Effects on animals

Animal studies have shown that several PFAS can impair immune response, disrupt normal endocrine function, and have negative effects on various organs, including the liver and pancreas. They have also been associated with developmental issues in rat pups exposed to them in the womb (Camdzic et al., 2022; Xinmou et al., 2017). Both animal and human research is necessary to gain a better understanding of the potential negative consequences of PFAS on human health.

Studies on animals provide compelling evidence that PFAS can have harmful health effects on animals, both early in life and as they age. Numerous impacts, including effects on development, thyroid and liver function, immune response, increased liver and kidney weight, and cellular alterations, have been observed in these studies. Animals exposed to extremely high doses of PFOA have also shown an increased incidence of tumours in various organs (Camdzic et al., 2022). These findings highlight the potential carcinogenic effects of PFAS exposure in animals.

Despite the limited understanding of the mechanisms underlying the adverse effects of PFAS on animals, the available evidence suggests that PFAS exposure can lead to a wide range of health impacts. Animals exposed to PFAS have exhibited developmental abnormalities, disruptions in thyroid and liver function, altered immune response, increased liver and kidney weight, and cellular changes (Camdzic et al., 2022). Additionally, certain PFAS, such as PFOA, have been associated with an elevated incidence of tumours in various organs (Camdzic et al., 2022).

4.2 Effects on humans

The health risks associated with PFAS exposure in humans have been a subject of growing concern. Due to their persistence in the environment and the human body, PFAS can pose significant risks to human health, affecting growth, lipid metabolism, the endocrine system, and potentially leading to cancer, immunotoxicity, hepatotoxicity, and nephrotoxicity (Fenton et al., 2021; Panieri et al., 2022).

One of the most notable effects of PFAS exposure is the increase in blood total cholesterol levels in adults and the decrease in antibody responses to vaccination in children (Panieri et al., 2022). PFOA has been associated with an increase in blood total cholesterol levels, while PFOA exposure has been linked to a decrease in birth weight (Panieri et al., 2022). Epidemiological studies have consistently shown that higher levels of PFAS exposure are associated with various adverse health effects, including elevated cholesterol, liver dysfunction, impaired immune function, thyroid disorders, and, in the case of PFOA, kidney and testicular cancer (ATSDR, 2022).

Researchers are actively investigating the potential links between PFAS exposure and other health outcomes. Some studies have explored the possible association between PFAS and behavioural disorders, such as attention deficit hyperactivity disorder (Harris et al., 2021; Vuong et al., 2021). Others have focused on understanding the effects of PFAS and other chemicals on immune system function and neuro-behavioural development (USEPA, 2022b). For instance, research has shown that increased PFAS exposure during development may result in reduced vaccine-induced immune protection in children (USEPA, 2022b).

The liver is a major target organ for PFAS accumulation, with evidence of toxicity observed across species, including hepatocyte fat infiltration, induction of specific P450 pathways, apoptosis, hepatocellular adenomas and carcinomas, and disrupted fatty acid trafficking (Yao et al., 2016; Guillette et al., 2020). PFAS exposure has also been linked to non-alcoholic fatty liver disease (NAFLD), and a clinic-based investigation found a higher prevalence of advanced NAFLD in obese children exposed to PFOS and PFAS (Jin et al., 2020).

Changes in lipid and glucose metabolism have also been associated with PFAS exposure, with inconsistent findings across studies. However, PFAS have been linked to metabolic syndrome and its components, and PFOS exposure has been positively associated with elevated glucose levels (Christensen et al., 2019; Preston et al., 2020). Experimental research suggests that PFAS can enhance insulin production and promote insulin resistance, indicating a potential impact on glucose metabolism (Qin et al., 2020; Zhang et al., 2020; Alderete et al., 2019; Lin et al., 2019).

Moreover, PFAS exposure has been shown to induce oxidative stress and damage DNA through the production of reactive oxygen species, potentially leading to tumour development (Shi and Zhou, 2020). Oxidative stress occurs when there is an imbalance between the production of reactive oxygen species and the body's ability to detoxify them. This oxidative stress can cause damage to cellular components, including DNA, proteins, and lipids, and has been implicated in various diseases, including cancer.

Studies have provided evidence of a potential link between PFAS exposure and cancer in humans. Some epidemiological studies have reported associations between PFAS exposure and increased risk of certain cancers, such as kidney, testicular, bladder, prostate, and ovarian cancer (ATSDR, 2022; Panieri et al., 2022). However, the evidence is still evolving, and more research is needed to establish a definitive causal relationship between PFAS exposure and cancer in humans.

The available evidence suggests that PFAS exposure can have detrimental effects on both animals and humans. Animal studies have demonstrated a wide range of adverse health outcomes, including developmental abnormalities, disrupted thyroid and liver function, altered immune response, and increased incidence of tumours. In humans, PFAS exposure has been associated with increased cholesterol levels, liver dysfunction, impaired immune function, thyroid disorders, and potential links to cancer.

It's important to note that the studies on PFAS and their health effects are still ongoing, and there is much more to learn about the long-term consequences of exposure. Regulatory bodies and researchers continue to investigate the risks associated with PFAS and work on strategies to mitigate their presence in the environment and reduce human exposure.

5.0 Treatment Mechanisms of Pfas

Due to the strong carbon-fluorine bonds in PFAS compounds, their breakdown in the environment poses a significant challenge. As a result of this slow degradation of PFAS, individuals and animals often experience prolonged exposure, leading to the accumulation of PFAS in their blood over time. Currently, substantial efforts are being made to reduce human exposure to these persistent and constantly changing chemicals through the development of rapidly evolving treatment techniques for PFAS removal. Although the efficacy and practicality of these techniques are occasionally controversial or costly, numerous treatment mechanisms have been discovered through scientific studies. However, these mechanisms have only achieved a limited level of PFAS elimination or destruction in the environment, including soil and water. Nevertheless, emerging water remediation techniques, such as adsorption, anionic exchange resins, advanced oxidation, and membrane-based approaches, are being cautiously explored.

In addition to water, various mechanisms have been employed to remove PFAS from soil. Immobilization, a notable aspect of corrective measures for PFAS-contaminated soils, has shown promise, although its long-term effectiveness remains a subject of investigation. Soil washing and thermal treatment have also been utilized; however, they are costly and demanding due to the requirement for large amounts of washing solvents and the high melting temperature of PFAS, respectively. Nevertheless, emerging techniques such as ball milling, chemical oxidation, and electron beams are currently being experimented with, as discussed by Mahinroosta and Senevirathna (2020).

5.1 Diverse Mechanisms and Technologies for PFAS Treatment

The growing recognition of perfluoroalkyl substances (PFAS) as emerging pollutants, coupled with increasingly stringent regulatory standards and declining water quality benchmarks in the parts per trillion range, has necessitated the development of effective treatment methods. PFAS compounds, known for their persistence and mobility, can form extensive plumes, contaminating soil and water over long distances (Ross et al., 2018). Traditional remediation techniques such as reduction, biological degradation, and physical processes like coagulation, sedimentation, or filtration have proven ineffective in eliminating PFAS, particularly perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA). This inefficacy can be attributed to the stable biophysical properties of these substances in ambient environments, as reported by Im et al. (2021) and Li et al. (2021). Chemical degradation under specific conditions and high temperatures are required for the complete destruction of PFAS. However, this process is often challenging and demanding (Lu et al., 2020).

To address these limitations, alternative methods have been extensively researched to evaluate their effectiveness in PFAS removal from soils and water. These include anionic exchange resin (AER), advanced oxidation and photocatalytic processes, adsorption technology using granular activated carbon (GAC), destructive technologies, and membrane technologies such as reverse osmosis and nanofiltration (Niu et al., 2017). While GAC is commonly used as a temporary treatment technique for PFAS removal in water, it has been found to be ineffective for short-chain PFAS and their precursors, making it suitable only for the elimination of longer-chain PFAS (Militao et al., 2022).

6.0 Explanation of Physical, Chemical and Biological Treatment Approaches for PFAS in Soil and Water Systems

The treatment methods for PFAS are numerous and can be applied based on different conditions and matrixes. In this review, treatment techniques such as nanofiltration, reverse osmosis, soil washing, ozonation, anion exchange resin, granular activated carbon (GAC), powdered activated carbon (PAC), electron beams, soil immobilization, and biological methods were reviewed, and their descriptions and limitations highlighted in table 2 below.

Table 2: Treatment Techniques for PFAS Remediation in Soil and Water Systems with Limitations

Treatment Technique	Description	Limitations	References
Physical Treatments			
Nanofiltration	Use of pressure-driven membranes with small pore size (1-10 nm)	High operational and maintenance costs, also requires pre-treatment to prevent membrane fouling	Ambaye et al., 2022
Reverse Osmosis (RO)	Utilizes pressure-driven semi-permeable membranes	High energy consumption. Requires pre-treatment to prevent membrane fouling	Kanchanapa and Tantisattaya (2022).
Soil Washing	Extraction of soil materials with extracting agents	May result in soil erosion and disturbance. Treatment of large volumes of soil can be challenging	Mahinroosta and Senevirathna (2020)

Treatment Technique	**Description**	**Limitations**	**References**
Ozofractionation	This technique utilizes ozone instead of air in foam fractionation and has been found to be effective for the removal of both lengthy and small PFAS	Effective for removing lengthy PFAS but not suitable for short-chain PFAS and their precursors.	Dia et al., (2019)
Sonolysis Technique	Often used in water matrix, this technique involves the use of high-frequency ultrasound waves to create acoustic cavitation.	Promising destructive technique in the laboratory, but scalability is limited.	Wanninayake, (2021).
Chemical Treatments			
Anion Exchange Resin	Using ion exchange methods, AER successfully remove a variety of PFAS contaminants from water by selectively trapping and exchanging anions.	Peripheral waste produced during resin renewal process. Performance affected by co-contaminants	Boyer et al. (2021); Dixit et al., (2021).
Granular Activated Carbon (GAC)	Utilizes electrostatic attractions and hydrophobic interactions	Limited effectiveness against short-chain PFAS. May lead to clogging in water treatment systems	Rodowa et al., 2020; Nadagouda and Lee (2021); Riegel et al., 2023
Powdered Activated Carbon (PAC)	More efficient than GAC due to increased surface area	Higher cost compared to GAC. Handling and disposal of powdered carbon can be challenging	Franke et al. (2021)
Immobilization (sorption and stabilization)	Application of sorbents to soil to disable PFAS	Effectiveness depends on the type and dosage of sorbents. Limited applicability to large-scale remediation projects	Bierbaum et al. (2023)
Chemical Oxidation Technique	Application of potent oxidizing agents, such as hydrogen peroxide or ozone, to break down PFAS compounds in soil or water, with consideration for potential byproducts and site-specific conditions.	High effectiveness in removing certain PFAS, but concerns about the formation of shorter-chain PFAS and the rebound of sorbed precursors during on-site application.	Banks et al., (2019)
Biological Methods			
Bioremediation using microorganisms	Utilizes various organisms for PFAS degradation	Requires favorable environmental conditions and nutrient availability. Limited information available on specific microorganisms for PFAS degradation	Shahsavari et al. (2021)
Phytoremediation	Investigating the use of plants, such as algae, for PFAS degradation	Limited understanding of plant-PFAS interactions. Efficiency varies depending on plant species and environmental factors	Shahsavari et al. (2021)

7.0 Advancements in PFAS Remediation: Integrating Novel Technologies for Enhanced Efficiency

The remediation of perfluoroalkyl substances (PFAS) presents significant challenges due to their strong chemical bonds, high stability, and unique physicochemical properties. Conventional remediation techniques, such as activated carbon, membrane filtration, and ion exchange, have been employed with varying degrees of success in removing PFAS from soil and water. However, these techniques have limitations in terms of selectivity and effectiveness, particularly when dealing with both long and short-chain PFAS.

To address these challenges, recent advancements in PFAS remediation have focused on integrating novel technologies that enhance the efficiency of existing methods.

7.1 Electrochemical Remediation

Electrochemical techniques, including electro sorption and electrochemical oxidation/reduction processes, have gained attention for their potential in PFAS removal. Santiago et al. (2022) conducted a study on electrochemical remediation of PFAS from water and demonstrated its effectiveness. Electrosorption involves the selective adsorption of PFAS onto an electrode surface under an applied electric potential. Electrochemical oxidation/reduction processes, on the other hand, aim to degrade PFAS through electrochemical reactions.

In a recent study by Sharma et al., (2022) the authors investigated the remediation of per- and polyfluoroalkyls (PFAS) using electrochemical methods. The research explored the latest developments and limitations in electrochemical treatment techniques for PFAS removal, with a focus on the use of boron-doped diamond (BDD) and titanium sub-oxide ceramic anodes, specifically Magnéli phase Ti4O7 electrodes, which have demonstrated nearly 99% PFAS removal efficiency with minimal energy consumption compared to other methods. The study addresses crucial aspects of PFAS remediation and offers valuable insights for future research and large-scale applications in environmental remediation.

Mirabediny et al., (2023) conducted a comprehensive review focusing on recent advancements in electrochemical oxidation (EO) methods for degrading per- and poly-fluoroalkyl substances (PFAS), highly stable and toxic fluorinated organic compounds of global environmental concern. The study critically assesses key parameters influencing EO efficacy, such as anode material, current density, solution pH, electrolyte, plate distance, and electrical connector type. It also discusses energy consumption, the impact of different PFAS functional groups, and water matrices on EO efficiency. The review underscores the need for cost-effective, environmentally friendly, and energy-efficient technologies to address the urgent challenge of PFAS remediation on a large scale. EO emerges as a promising approach, characterized by its high energy efficiency, scalability, and minimal chemical usage.

These electrochemical remediation approaches offer several advantages, including high removal efficiency, rapid treatment, and the potential for in-situ application. However, challenges remain in terms of the development of cost-effective and scalable electrode materials, optimization of operational parameters, and management of potential by-products.

7.2 Nano remediation

Nano remediation technologies utilizing nanoscale materials have shown promise in the remediation of various contaminants, including PFAS. Ganie et al. (2021) discussed the recent advances and challenges in nano remediation technologies for sustainable remediation of contaminated environments. Nano sensors based on nanoparticles have emerged as highly sensitive tools for PFAS detection. These sensors, integrated with in-situ monitoring platforms, enable real-time and accurate detection of PFAS concentrations in environmental matrices. Moreover, nanoparticles can be functionalized to exhibit sorption properties, making them effective adsorbents for PFAS removal. The large surface area and high reactivity of nanoparticles facilitate the adsorption of PFAS from soil and water matrices. Additionally, nanoparticles can be used in conjunction with other remediation techniques, such as activated carbon, to enhance their adsorption capacity and selectivity for PFAS.

In a recent study (Zhang et al., 2021), the removal of PFAS (Per- and polyfluoroalkyl substances) using in-situ formed ferric nanoparticles through ozonation was explored. The research found that the size of these nanoparticles was influenced by factors like ferrous dose, pH, and ozone exposure time. The highest PFAS removal achieved was 44%, and the PFAS solid phase loading on the nanoparticles reached 80%. However, it was noted that achieving the highest PFAS removal and the highest solid phase loading simultaneously was challenging under the experimental conditions.

In Deng et al.'s (2012) study, various carbon nanotubes (CNTs) were examined for their ability to adsorb perfluorooctanoic acid (PFOA). These CNTs included single-walled and multiwalled types with different outer diameters, as well as functionalized CNTs. Sorption isotherms showed that SWCNT and MWCNT-10 had higher PFOA adsorption than MWCNT-20, MWCNT-40, and MWCNT-100. Hydrophobic interactions were the primary sorption mechanism, resulting in adsorbed PFOA amounts lower than 0.23 mmol/g for equilibrium concentrations below 0.75 mmol/L. In contrast, oxidized CNTs with hydrophilic groups exhibited lower sorption for PFCs, indicating the significance of CNT properties in PFOA removal (Deng et al., 2012).

While nano remediation holds great potential, challenges such as nanoparticle stability, potential toxicity, and long-term environmental impacts need to be addressed. Furthermore, the scale-up and cost-effectiveness of nano remediation technologies require further research and development.

7.3 Gasification and pyrolysis

Gasification and pyrolysis stand out as effective thermochemical processes for addressing PFAS contamination, involving the application of high temperatures (500-850°C) in the absence of oxygen. This thermal treatment induces the decomposition of PFAS into smaller, less harmful molecules, capitalizing on their relatively low thermal stability. Notably, the carbon-fluorine bond, the strongest in the PFAS molecule, succumbs to these elevated temperatures, distinguishing these methods from alternative approaches like incineration, hydrothermal liquefaction, and thermal hydrolysis.

A review by Garg et al., (2023) considered different thermal techniques such as incineration, hydrothermal liquefaction, pyrolysis, and thermal hydrolysis in PFAS removal in biosolids basically from activated sludges from wastewater and discovered that few parched thermal treatment approaches operate at extremely harsh parameters of 300–900 °C with a lime amendment for PFOS removal. PFAS can readily decompose at high temperatures resulting in the release of harmful fluorocarbon gases.

Munson's (2023) study on PFAS destruction in wastewater solids, commissioned by the Minnesota Pollution Control Agency (MPCA), revealed significant findings regarding the application of pyrolysis. The research aimed to assess commercially available technologies for PFAS removal and destruction in biosolids. Munson identified pyrolysis, coupled with thermal oxidation of the process gas, as a promising technology for consistently removing PFAS below laboratory detection limits. The study highlighted pyrolysis as a viable PFAS destruction method, emphasizing its effectiveness in wastewater solids. Moreover, Munson's findings indicated that the operation and maintenance costs per dry ton for pyrolysis trended lower as the system capacity increased. This observation suggests that smaller utilities could potentially reduce costs by adopting pyrolysis and forming regional partnerships for PFAS destruction.

These techniques offer advantages in terms of both PFAS destruction and the generation of useful end products. The inherent resistance of PFAS to traditional remediation methods makes gasification and pyrolysis attractive, as these processes can achieve higher destruction efficiencies. Furthermore, the versatility of gasification and pyrolysis allows them can be used to treat a wide range of environmental matrices, including water, soil, sediment, and biosolids. This makes them a versatile and adaptable remediation technology for PFAS. These advancements mark significant progress in developing environmentally friendly strategies for tackling the challenges associated with PFAS contamination.

The study conducted by Berg et al., (2022) in association with the U.S. Environmental Protection Agency's Office of Research and Development (ORD) commissioned the PFAS Innovative Treatment Team (PITT) to address the pressing issue of PFAS contamination. This six-month project aimed to identify innovative treatment technologies for PFAS-containing wastes, and among the four selected technologies, gasification and pyrolysis emerged as promising contenders. The research examined the mechanisms of pyrolysis and gasification, emphasizing their ability to decompose solid or semi-solid materials at high temperatures in an oxygen-free environment. The study emphasized the potential of generating hydrogen-rich synthetic gas (syngas) through these processes, highlighting the prospect of destroying PFAS by breaking them into inert or less recalcitrant constituents.

7.4 Supercritical water oxidation

Supercritical water oxidation (SCWO) is an advanced oxidation process that involves the treatment of organic compounds in water at extremely high temperatures and pressures, typically above the critical point of water (374°C and 22.1 MPa). SCWO offers a potential solution by subjecting PFAS to extreme conditions, breaking down these robust bonds and converting them into simpler, less harmful byproducts.

In their study, Krause et al. (2021) investigated Supercritical Water Oxidation (SCWO) as a potential treatment for per- and polyfluoroalkyl substances (PFAS). Operating under extreme conditions, SCWO demonstrated over 99% reduction in PFAS concentrations, including significant compounds like PFOS and PFOA, in dilute aqueous film-forming foam (AFFF) solutions. Post-treatment, chemical oxygen demand in AFFF significantly decreased, indicating effective destruction of organic compounds. Mass balance analysis revealed the limitation of relying solely on targeted analysis. SCWO emerged as a robust alternative to incineration, offering a potential permanent solution for PFAS-laden wastewaters.

Li et al. (2023) assessed SCWO for PFOS treatment, employing a continuous flow reactor at temperatures from 410 °C to 650 °C. Liquid Chromatography-Tandem Mass Spectrometry (LC-MS/MS) analysis revealed PFOS degradation through C-S bond cleavage, decarboxylation, and -CF2 elimination. Trifluoroacetic acid (TFA) persisted as a challenging intermediate, emphasizing the need for monitoring. Gaseous product analysis detected volatile organofluorine (VOF), and ion chromatography confirmed complete PFOS defluorination at 650 °C. The study established SCWO's efficacy, outlining operational parameters and chemical pathways, while underscoring the importance of characterizing intermediate species for a comprehensive understanding of PFAS destruction in SCWO environments.

McDonough et al. (2022) conducted a pivotal study on the application of Supercritical Water Oxidation (SCWO) for treating concentrated waste streams containing 12 perfluoroalkyl acids (PFAAs). Their research demonstrated SCWO's efficacy with a remarkable destruction and removal efficiency exceeding 99.999% for all 12 PFAAs. The study revealed a defluorination percentage of approximately 62.6%, highlighting SCWO's potential for PFAS waste stream management. Notable findings included minimal residual PFAAs concentrations in both liquid and gaseous effluents, emphasizing SCWO's promise as a highly effective solution for PFAS remediation. SCWO is a promising technology for PFAS destruction, offering significant advantages over traditional incineration methods. SCWO research is advancing rapidly, with recent studies demonstrating its efficacy for treating a wide range of PFAS-laden wastes. While further research and development are needed, SCWO is poised to play a significant role in addressing the global PFAS crisis.

7.5 Advanced Oxidation Processes (AOPs)

The degradation of organic pollutants in water bodies is a critical concern for environmental sustainability. Traditional water treatment methods often fall short in effectively removing recalcitrant contaminants. In response to this challenge, advanced oxidation processes (AOPs) have emerged as promising techniques for the degradation of persistent organic pollutants. AOPs involve the generation of highly reactive hydroxyl radicals (OH^{-}) that efficiently break down complex organic compounds. Among the various AOPs explored, photocatalysis has gained significant attention.

Photocatalysis, as an advanced oxidation process, employs semiconductors such as titanium dioxide (TiO2) to generate reactive oxygen species under UV or visible light. The photocatalytic degradation of pollutants has been widely investigated. In a study by Ahmed et al. (2020), TiO2 photocatalysis demonstrated high efficiency in degrading pharmaceutical compounds, emphasizing its potential for water treatment applications. Furthermore, the work of Dolai et al., (2022) expanded the scope of photocatalysis by exploring novel materials like graphitic carbon nitride for enhanced photoactivity.

Sonolysis, another AOP, involves the use of ultrasound waves to induce cavitation, generating free radicals that contribute to pollutant degradation. In the research conducted by Kulkharni et al. (2022), a mobile treatment system equipped with a sonolysis reactor resulted in the removal of 93% to 100% of 15 PFAS compound that were identified in groundwater samples showcasing its efficiency in the removal of PFAS compounds. Additionally, Kalra et al., (2021) utilized sonolysis in the removal of 7 PFAS compound in groundwater samples containing 24 mix of PFAS compounds and recorded 30 to 60% removal rate, providing insights into optimizing sonolytic processes for enhanced pollutant removal.

Electrochemical advanced oxidation processes represent a promising avenue for water treatment. Electro-Fenton, for instance, utilizes electro-generated OH^{-} radicals for pollutant degradation. The study Olvera-Vargas et al., (2022) focused on hexafluoropropylene oxide dimer acid (GenX), a short-chain PFAS, using an electro-Fenton (EF) process with a graphene-Ni-foam cathode and a boron-doped diamond (BDD) anode. The study revealed a notable efficiency in the mineralization of GenX, particularly when synergizing EF with BDD oxidation. With a remarkable 92.2 ± 1.0% GenX mineralization achieved after 6 hours of treatment at 16 mA cm−2, surpassing outcomes with EF alone (9.2 ± 0.1%) and BDD alone (73.6 ± 6.2%), the electrochemical method demonstrated promising efficacy in addressing the environmental impact of emerging PFAS contaminants like GenX.

The adaptability of AOPs to diverse water matrices and the capacity to target a wide range of PFAS compounds make them a robust option for remediation efforts. As a non-selective and powerful treatment method, AOPs present a valuable approach in addressing the challenges posed by PFAS contamination in various environmental settings.

7.6 Activated Carbon Adsorption

Activated carbon adsorption (AC adsorption) stands as a promising and emerging technique for treatment of PFAS in soil and water systems. In the quest for effective PFAS removal methods, AC adsorption offers distinct advantages, including its high removal efficiency, versatility, and scalability. Capable of effectively removing a broad spectrum of PFAS compounds, ranging from short-chain to long-chain and branched-chain varieties, AC adsorption finds applicability in treating various PFAS-contaminated matrices, encompassing water, soil, sediment, and wastewater. The flexibility of AC adsorption systems is evident in their diverse configurations, such as fixed-bed and fluidized-bed adsorbers, with performance influenced by factors like the type of AC used, PFAS characteristics, and operating conditions (Vu et al., 2022; Chaudhary et al., 2022). While AC adsorption systems are designed to achieve removal efficiencies of 90% or greater, it is crucial to acknowledge that they are not flawless solutions, as saturation over time necessitates replacement or regeneration of the AC.

Ramos et al. (2022) examined the efficiency of granular activated carbon (GAC) in removing PFASs from complex industrial waters by surface modification with polyDADMAC-coated regenerable granular activated carbon (GAC). Even at low concentrations, polyDADMAC significantly enhanced GAC's PFAS adsorption, addressing challenges posed by short-chained PFASs and co-contaminants. The study emphasized optimal polymer dosage to maintain effectiveness. Furthermore, a proposed regeneration method using low-power ultrasound demonstrated successful PFAS desorption, ensuring the adsorbent's viability over multiple cycles. This research highlights polyDADMAC-modified GAC as a potent and regenerable adsorbent for efficient PFAS removal in challenging real-world conditions.

In their study, McCleaf et al., (2017) reviewed the efficiency of granular activated carbon (GAC, Filtrasorb® 400) and anion exchange (AE, Purolite® A600) for PFAS from drinking water. Examining 14 PFASs over 217 days, the study revealed a selective removal pattern influenced by perfluorocarbon chain length, functional group, and isomer structure. Shorter-chained PFASs exhibited desorption, while longer-chained ones showed increased removal, possibly due to agglomeration. Linear isomers displayed superior removal efficiencies.

In another study, McGregor (2018) investigated the effectiveness of colloidal activated carbon in treating PFAS in a shallow anaerobic aquifer in Canada. PFASs, the concentrations of PFAS in the aquifer according to the study exceeded health-based regulatory criteria, with concentrations up to 3,260 ng/L for PFOA and 1,450 ng/L for PFOS. In this study, colloidal activated carbon was applied using direct-push technology, resulting in PFOA and PFOS concentrations below 30 ng/L over 18 months. Only two PFAS compounds, perfluoroundecanoic acid (20 ng/L) and perfluorooctanesulfonate (40 ng/L), were detected after 18 months. The successful distribution of colloidal activated carbon within the aquifer suggests its efficacy in addressing low to moderate PFAS concentrations in similar environments.

7.7 Integration of Advanced Technologies

The integration of advanced technologies, such as electrochemical remediation and nanoremediation, with conventional techniques, holds promise for overcoming the limitations of individual methods. For instance, electrochemical techniques can be combined with sorption-based approaches using functionalized nanoparticles, enabling simultaneous adsorption and degradation of PFAS.

Furthermore, the integration of in-situ sensors based on electrochemical or nanosensor platforms can provide real-time monitoring of PFAS concentrations during the remediation process. This allows for better control and optimization of treatment operations, ensuring effective and efficient remediation.

Other recent treatment techniques have shown promising results. Table 3 summarizes some notable techniques and their application in PFAS remediation:

Table 3: Recent Technological Advances in the Remediation of PFAS Contamination

Remediation technique	Remediation site	Mechanism/function	Reference
1. Powdered Moringa oleifera seed combined with calcium alginate beads.	Ex situ, water	This adsorption technique adsorbs perfluorobutanesulfonic acid (PFBS) and perfluorooctanesulfonic acid (PFOS). The duo is commonly found in PFAS-contaminated water. The beads have a high PFOS adsorption capacity and quick kinetics, reaching equilibrium in 30 minutes.	Militao et al., (2022)
2. Foam fractionation	In-situ, water	Foam fractionation makes use of the surfactant capabilities of PFAS to produce a PFAS-enriched foam (because of the hydrophilic head group and a hydrophobic tail of PFAS) that is simple to remove.	Meegoda et al., (2020); Karidis, (2022).
3. Ceric (IV) ammonium nitrate	In-situ, water	Ceric (IV) ammonium nitrate is another novel method for precipitating PFOS from water. According to the report, PFAS can be oxidatively degraded in situ using nanoparticles produced from $CoCl_2$ and $FeCl_2$ and mixed valent or high valent oxide species. The PFAS content in the supernatant aqueous solution reduced significantly when ceric(IV) ammonium nitrate was used as an oxidant.	Sun et al., (2021)

4.	Contact plasma reactor	Ex-situ, water	This plasma-based method uses aqueous electrons, plasma electrons, and argon ions to break down PFOS and PFOA into perfluoroalkyl radicals. This apparatus quantified both the gas and liquid phase by-products generated during PFAS breakdown. Using the fluorine mass balance, it was discovered that the parent PFOS and PFOA, respectively, are responsible for about 23% and 42% of the fluorine by-products, which were adsorbed onto the reactor walls.	Olsavsky et al., (2020)
5.	Phytoremediation	In-situ, soil	Several plants are capable of bioaccumulating PFAS. Although phytoremediation cannot break down PFAS, bioaccumulation in plants presents a prospective pathway for the elimination of PFAS from polluted sites. Plants like *Betula pendula, Picea abies* and the wetland species of *Juncus effuses* have been found effective.	Shahsavari et al., (2021)
6.	Microbial remediation	In-situ, soil, landfill where solid waste is disposed	This is the use of a biological agent to break down contaminants. There have been isolated bacterial and fungal strains that can break down PFAS. However, Ji et al. (2020) proposed that microbial remediation be utilized in conjunction with other bioremediation approaches for time effectiveness because this method is quite extremely slow.	Ji et al., (2020); Shahsavari et al., (2021).
7.	Membrane separation	In-situ, wastewater	For a variety of PFAS, membranes have been demonstrated to have superior removal capabilities. The removal capacity of membranes is not constrained by the concentration of salts, co-contaminant or organic matter, presence because the selectivity of membrane is determined by its surface properties, such as pore size, permeability, material and zeta potential.	Tow et al., (2021); Das and Ronen, (2022).
8.	High and low-frequency ultrasound	Ex-situ, Soil, and solid waste	This sonication treatment is an active method for removing PFAS from solids, it can be severely impacted by the particulate matters in the solid-liquid slurry, which prevents the sonolytic breakdown of desorbed PFAS. PFOS PFOA were utilized to assess treatment effectiveness in soils with both high and low amounts of organic matter. The results proved that the ultrasound treatment may dramatically lower the levels of PFAS in soil that had been chemically contaminated, but no apparent degradation was attained.	Kewalramani et al., (2022)

9.	Cross-linked chitosan beads	Ex-situ groundwater	This can adsorb PFOS more effectively at pH 3. A very high percentage of the amino groups in the chitosan beads were protonated when the pH of the test solution was lowered to 3.0. As a result, the negatively charged PFOS was easily adsorbed, leading to an increase in its removal. At an equilibrium concentration of 0.33 mmol/L, the final sorption capacity of the improved chitosan biosorbent was found to be up to 5.5 mmol/g for PFOS, which is significantly higher than that of conventional absorbents.	Kucharzyk et al., (2017).
10.	Single-welled carbon nanotubes and maize ash	Ex-situ groundwater	This possesses significant PFOS adsorption capabilities (above 700 mg/g) as a result of the production of hemimicelles and hydrophobic interactions that encourage PFOS adhesion.	Chen et al., (2011).
11.	Smouldering combustion	In-situ and ex-situ, soil	Smouldering is a novel thermal PFAS remediation technique. It is a highly cost and energy efficient treatment method. It is a flameless oxidation reaction that occurs on the surface of a liquid or solid fuel when penetrated by gaseous oxygen. Additionally, it requires no external energy input to convert the carbonaceous fuel to carbon dioxide heat and water.	Duchesne et al., (2020)

These recent technological advancements highlight the continuous efforts to develop innovative approaches for PFAS remediation. However, it is important to critically evaluate the limitations, applicability, and potential environmental impacts associated with each technique. Further research and development are needed to optimize these approaches and ensure their effectiveness in addressing PFAS contamination.

The remediation of PFAS is a complex task due to the unique characteristics of these substances. Recent advancements have focused on sensitive detection methods, such as sensor platforms and nano-sensors, as well as novel remediation techniques, including adsorption, chemical oxidation.

8.0 Future Perspectives

The field of perfluoroalkyl substances (PFAS) remediation is continuously evolving, and future research and development efforts hold promise for further advancements in addressing PFAS contamination.

8.1 Exploration of Combined Treatment Strategies

To improve treatment efficiency, reduce energy consumption, minimize costs, and enhance sustainability, it is crucial to explore the integration of multiple strategies in a treatment train. Currently, there are limited treatment options for remediating PFAS-contaminated soil, and the majority of available technologies primarily focus on drinking water and groundwater remediation (Kewalramani et al., 2022). However, combining different approaches such as sequestration technologies and destruction technologies can offer more effective solutions.

For instance, the combination of electrochemical, plasma, sonolytic, or hydrothermal processes with ion exchange has shown promise in PFAS removal (Meegoda et al., 2020; Verma et al., 2021). By integrating these technologies, the limitations of individual methods can be overcome, resulting in improved treatment outcomes.

8.2 Synergistic Approaches in Built Wetlands

The potential for synergistic approaches should also be explored, particularly in the context of built wetlands. Combining phytoremediation, which utilizes plants to remove contaminants, with PFAS-degrading bacteria in a built wetland has shown promise for the removal of various pollutants, including pesticides, pharmaceuticals, and personal care items (Liu et al., 2019). Such synergistic approaches can enhance the environmental friendliness and efficiency of PFAS remediation strategies.

8.3 Integration of Advanced Tools in Bioremediation

Recent studies have highlighted the impact of polyfluorinated alkyl substances on microbial communities, opening avenues for the use of advanced tools in bioremediation efforts. Metabolomics, stable isotope probing, metagenomics, and transcriptomics have been proposed as useful tools in the bioremediation of xenobiotics like PFAS in synthetic biology (Cai et al., 2020; Rylott and Bruce, 2020; Shahsavari et al., 2021). These tools can provide valuable insights into the mechanisms and pathways involved in PFAS degradation, enabling more targeted and efficient bioremediation strategies.

8.4 Addressing Knowledge Gaps

Despite significant progress in PFAS remediation research, there are still knowledge gaps that need to be addressed. Further investigations are needed to better understand the long-term effectiveness and potential secondary impacts of different treatment approaches. Additionally, research should focus on developing standardized protocols for monitoring and assessing the performance of PFAS remediation technologies to ensure their reliability and comparability.

Furthermore, there is a need for studies that evaluate the scalability and practical implementation of emerging PFAS treatment technologies. Considering the complexity and persistence of PFAS, research efforts should be directed toward developing cost-effective and sustainable large-scale remediation techniques that can be applied in various environmental settings.

The future of PFAS remediation lies in the exploration of combined treatment strategies, synergistic approaches in built wetlands, integration of advanced tools in bioremediation, and addressing knowledge gaps. By focusing on these areas, researchers and practitioners can contribute to the development of more efficient, sustainable, and reliable technologies for the remediation of PFAS-contaminated environments.

9.0 Conclusion

The remediation of perfluoroalkyl substances (PFAS) poses a significant challenge due to their persistence, mobility, and potential adverse effects on human health and the environment. Conventional treatment methods have proven inadequate in completely eliminating PFAS from soil and water systems, necessitating the exploration of novel and integrated approaches. This research has provided an overview of various physical, chemical, and biological techniques that have been investigated for PFAS removal. These techniques, however, have their limitations, including high operational costs, limited effectiveness against short-chain PFAS, challenges in treating small PFAS, and the potential formation of unwanted byproducts. Despite these challenges, recent advancements offer promise in addressing these limitations and improving the overall efficiency of PFAS remediation. Electrochemical remediation techniques, such as electrosorption and electrochemical oxidation/reduction processes, have demonstrated high removal efficiency and rapid treatment of PFAS. Nanoremediation technologies that utilize nanoparticles have shown potential in enhancing adsorption capacity and selectivity for PFAS. Integration of advanced technologies, such as electrochemical remediation and nanoremediation, with conventional techniques presents opportunities for improved remediation efficiency. Further research and development efforts are necessary to optimize these innovative techniques and overcome their limitations. Exploring combined treatment strategies, where multiple remediation approaches are integrated in a treatment train, can lead to enhanced outcomes. Synergistic approaches in built wetlands, combining phytoremediation and PFAS-degrading bacteria, hold promise for more effective PFAS removal. The integration of advanced tools, such as metabolomics and metagenomics, can provide valuable insights into PFAS degradation mechanisms and enable targeted bioremediation strategies. Addressing knowledge gaps is crucial, including understanding the long-term effectiveness, potential secondary impacts, scalability, and practical implementation of emerging PFAS treatment technologies. Standardized protocols for monitoring and assessing the performance of remediation techniques are essential to ensure reliability and comparability of results. The future of PFAS remediation lies in the continued exploration of innovative approaches, integration of different strategies, and collaboration between researchers and practitioners. By focusing on combined treatment strategies, synergistic approaches, advanced tools, and addressing knowledge gaps, more efficient, sustainable, and reliable technologies can be developed for the remediation of PFAS-contaminated environments. These advancements are vital in safeguarding human health and the environment from the adverse effects of PFAS contamination.

References

Abunada, Z., Alazaiza, M. Y., & Bashir, M. J. (2020). An overview of per-and polyfluoroalkyl substances (PFAS) in the environment: source, fate, risk and regulations. Water, 12(12), 3590. **https://doi.org/10.3390/w12123590**

Ahmed, M. B., Alam, M. M., Zhou, J. L., Xu, B., Johir, M. A. H., Karmakar, A. K., Rahman, M. S., Hossen, J., Hasan, A. T. M. K., & Moni, M. A. (2020). Advanced treatment technologies efficacies and mechanism of per-and poly-fluoroalkyl substances removal from water. *Process Safety and Environmental Protection*, *136*, 1-14. https://doi.org/10.1016/j.psep.2020.01.005

Ahrens, L., Rakovic, J., Ekdahl, S., & Kallenborn, R. (2023). Environmental distribution of per- and polyfluoroalkyl substances (PFAS) on Svalbard: Local sources and long-range transport to the Arctic.

Chemosphere, 345, 140463. https://doi.org/10.1016/j.chemosphere.2023.140463

Ahrens, L., Shoeib, M., Harner, T., Lee, S. C., Guo, R., & Reiner, E. J. (2011). Wastewater treatment plant and landfills as sources of polyfluoroalkyl compounds to the atmosphere. Environmental science & technology, 45(19), 8098-8105.doi: https://doi.org/10.1021/es1036173

Alderete, T. L., Jin, R., Walker, D. I., Valvi, D., Chen, Z., Jones, D. P., & Chatzi, L. (2019). Perfluoroalkyl substances, metabolomic profiling, and alterations in glucose homeostasis among overweight and obese Hispanic children: A proof-of-concept analysis. Environment international, 126, 445-453.

Ambaye, T. G., Vaccari, M., Prasad, S., & Rtimi, S. (2022). Recent progress and challenges on the removal of per- and poly-fluoroalkyl substances (PFAS) from contaminated soil and water. *Environmental Science and Pollution Research*, *29*(39), 58405-58428.https://doi.org/10.1007/s11356-022-21513-2

Ankley, G. T., Cureton, P., Hoke, R. A., Houde, M., Kumar, A., Kurias, J., Lanno, R., McCarthy, C., Newsted, J., Salice, C. J., Sample, B. E., Sepúlveda, M. S., Steevens, J., & Valsecchi, S. (2021). Assessing the Ecological Risks of Per- and Polyfluoroalkyl Substances: Current State-of-the Science and a Proposed Path Forward. *Environmental toxicology and chemistry*, *40*(3), 564–605. https://doi.org/10.1002/etc.4869

ATSDR. (2022). Per- and Polyfluoroalkyl substances (PFAS) and our Health. Potential Helath Effects of PFAS Chemicals. Agency for Toxic Substances and Disease Registry. U.S. Department of Health Services USA.gov. https://www.atsdr.cdc.gov.

Bai, X., & Son, Y. (2021). Perfluoroalkyl substances (PFAS) in surface water and sediments from two urban watersheds in Nevada, USA. Science of the Total Environment, 751, 141622. https://doi.org/10.1016/j.scitotenv.2020.141622.

Banks, D., Jun, B.-M., Heo, J., Her, N., Min Park, C., & Yoon, Y. (2019). Selected advanced water treatment technologies for perfluoroalkyl and polyfluoroalkyl substances: A review. Separation and Purification Technology, 115929. doi:10.1016/j.seppur.2019.115929

Barlow. C. A., Boyd. C. A., Kemp. M. J., & Purr. K. A. (2019). PFAS Toxicology - What is Driving the Variation in Drinking Water Standards. GZA Environmental, Inc. https://www.gza.com.

Bassler, J., Ducatman, A., Elliott, M., Wen, S., Wahlang, B., Barnett, J., & Cave, M. C. (2019). Environmental perfluoroalkyl acid exposures are associated with liver disease characterized by apoptosis and altered serum adipocytokines. Environmental pollution, 247, 1055-1063.

Berg, C., Crone, B., Gullett, B., Higuchi, M., Krause, M. J., Lemieux, P. M., Martin, T., Shields, E. P., Struble, E., Thoma, E., & Whitehill, A. (2022). Developing innovative treatment technologies for PFAS-containing wastes. *Journal of Air & Waste Management Association*, 72(6), 540–555. https://doi.org/10.1080/10962247.2021.2000903

Berhanu, A., Mutanda, I., Taolin, J., Qaria, M. A., Yang, B., & Zhu, D. (2023). A review of microbial degradation of per- and polyfluoroalkyl substances (PFAS): Biotransformation routes and enzymes. Science of The Total Environment, 859(Part 1), 160010. https://doi.org/10.1016/j.scitotenv.2022.160010

Beškoski, V. P., Yamamoto, K., Yamamoto, A., Okamura, H., Hayashi, M., Nakano, T., & Inui, H. (2017). Distribution of perfluoroalkyl compounds in Osaka Bay and coastal waters of Western Japan. Chemosphere, 170, 260-265.

Beylich, A.A. (2011). Sediment Flux Source-To-Sink. In: Singh, V.P., Singh, P., Haritashya, U.K. (eds) Encyclopedia of Snow, Ice and Glaciers. Encyclopedia of Earth Sciences Series. Springer, Dordrecht. https://doi.org/10.1007/978-90-481-2642-2_642.

Bierbaum, T., Klaas, N., Braun, J., Nürenberg, G., Lange, F. T., & Haslauer, C. (2023). Immobilization of per- and polyfluoroalkyl substances (PFAS): Comparison of leaching behavior by three different leaching tests. Science of The Total Environment, 876, 162588. https://doi.org/10.1016/j.scitotenv.2023.162588

Bierbaum, T., Klaas, N., Braun, J., Nürenberg, G., Lange, F. T., & Haslauer, C. (2023). Immobilization of per- and polyfluoroalkyl substances (PFAS): Comparison of leaching behavior by three different leaching tests. Science of The Total Environment, 876, 162588. https://doi.org/10.1016/j.scitotenv.2023.162588

Boisacq, P., De Keuster, M., Prinsen, E., Jeong, Y., Bervoets, L., & Eens, M. (2023). Assessment of poly- and perfluoroalkyl substances (PFAS) in commercially available drinking straws using targeted and suspect screening approaches. Food Additives & Contaminants: Part A, 40(9), 1230-1241. https://doi.org/10.1080/19440049.2023.2240908

Bolan, N., Sarkar, B., Vithanage, M., Singh, G., Tsang, D. C., Mukhopadhyay, R., & Kirkham, M. B. (2021a). Distribution, behaviour, bioavailability and remediation of poly-and per-fluoroalkyl substances (PFAS) in solid biowastes and biowaste-treated soil. *Environment international*, *155*, 106600. https://doi.org/10.1016/j.envint.2021.106600

Bolan, N., Sarkar, B., Yan, Y., Li, Q., Wijesekara, H., Kannan, K., Tsang, D. C. W., Schauerte, M., Bosch, J., Noll, H., Ok, Y. S., Scheckel, K., Kumpiene, J., Gobindlal, K., Kah, M., Sperry, J., Kirkham, M. B., Wang, H., Tsang, Y. F., Hou, D., & Rinklebe, J. (2021b). Remediation of poly- and perfluoroalkyl substances (PFAS) contaminated soils – To mobilize or to immobilize or to degrade? Journal of Hazardous Materials, 401, 123892. https://doi.org/10.1016/j.jhazmat.2020.123892

Brunn, H., Arnold, G., Körner, W., Rippen, G., Steinhäuser, K. G., & Valentin, I. (2023). PFAS: forever chemicals—persistent, bioaccumulative and mobile. Reviewing the status and the need for their phase out and remediation of contaminated sites. Environ Sci Eur 35, 20. https://doi.org/10.1186/s12302-023-00721-8.

Burns, D. C., Ellis, D. A., Li, H., McMurdo, C. J., & Webster, E. (2008). Experimental p K a determination for perfluorooctanoic acid (PFOA) and the potential impact of p K a concentration dependence on laboratory-measured partitioning phenomena and environmental modeling. Environmental science & technology, 42(24), 9283-9288. https://doi.org/10.1021/es802047v.

Cai, L., Hu, J., Li, J., Cao, X., Lyu, Y., & Sun, W. (2022). Occurrence, source apportionment, and pollution assessment of per-and polyfluoroalkyl substances in a river across rural and urban areas. *Science of The Total Environment*, *835*, 155505. https://doi.org/10.1016/j.scitotenv.2022.155505

Cai, Y., Chen, H., Yuan, R., Wang, F., Chen, Z., & Zhou, B. (2020). Metagenomic analysis of soil microbial community under PFOA and PFOS stress. Environ. Res. 188:109838.

Camdzic. M., Aga. D.S. & Atilla-Gokcumen. G.E. (2022). Cellular Interactions and Fatty Acid Transporter CD36-Mediated Uptake of Per- and Polyfluorinated Alkyl Substances (PFAS). Journal of Chemical Research in Toxicology, 35: 4.

Campos-Pereira, H., Makselon, J., Kleja, D. B., Prater, I., Kögel-Knabner, I., Ahrens, L., & Gustafsson, J. P. (2022). Binding of per-and polyfluoroalkyl substances (PFASs) by organic soil materials with different structural composition–Charge-and concentration-dependent sorption behavior. Chemosphere, 297, 134167. https://doi.org/10.1016/j.chemosphere.2022.134167

Chaudhary, M., Jain, N., Barman, L., & Bhowmick, G. D. (2022). Design and principles of adsorbent-based reactors for modular wastewater treatment. In *Modular Treatment Approach for Drinking Water and Wastewater* (pp. 129-148). Elsevier. https://doi.org/10.1016/B978-0-323-85421-4.00018-8

Chen, H., Zhang, L., Li, M., Yao, Y., Zhao, Z., Munoz, G., & Sun, H. (2019). Per-and polyfluoroalkyl substances (PFASs) in precipitation from mainland China: Contributions of unknown precursors and short-chain (C2C3) perfluoroalkyl carboxylic acids. *Water Research*, *153*, 169-177. https://doi.org/10.1016/j.watres.2019.01.019

Chen, X., Xia, X., Wang, X., Qiao, J., & Chen, H. (2011). A comparative study on sorption of perfluorooctane sulfonate (PFOS) by chars, ash, and carbon nanotubes. Chemosphere, 83, 1313-1319.

Chirikona, F., Quinete, N., Gonzalez, J., Mutua, G., Kimosop, S., & Orata, F. (2022). Occurrence and distribution of per-and polyfluoroalkyl substances from multi-industry sources to water, sediments and plants along Nairobi River basin, Kenya. International Journal of Environmental Research and Public Health, 19(15), 8980.

Christensen, K. Y., Raymond, M., & Meiman, J. (2019). Perfluoroalkyl substances and metabolic syndrome. International journal of hygiene and environmental health, 222(1), 147-153.

Comber, S. D. W., Gardner, M. J., & Ellor, B. (2021). Perfluorinated alkyl substances: Sewage treatment and implications for receiving waters. *Science of The Total Environment*, *791*, 148391. https://doi.org/10.1016/j.scitotenv.2021.148391

Crone, B. C., Speth, T. F., Wahman, D. G., Smith, S. J., Abulikemu, G., Kleiner, E. J., & Pressman, J. G. (2019). Occurrence of per-and polyfluoroalkyl substances (PFAS) in source water and their treatment in drinking water. Critical reviews in environmental science and technology, 49(24), 2359-2396. https://doi.org/10.1080/10643389.2019.1614848.

Dai, X., Xie, Z., Dorian, B., Gray, S., & Zhang, J. (2019). Comparative study of PFAS treatment by UV, UV/ozone, and fractionations with air and ozonated air. Environmental Science: Water Research & Technology, 5(11), 1897-1907.DOI:10.1039/C9EW00701F

Dalahmeh, S., Tirgani, S., Komakech, A. J., Niwagaba, C. B., & Ahrens, L. (2018). Per- and polyfluoroalkyl substances (PFASs) in water, soil and plants in wetlands and agricultural areas in Kampala, Uganda. *Science of The Total Environment, 631–632*, 660-667. https://doi.org/10.1016/j.scitotenv.2018.03.024

Dasu, K., Xia, X., Siriwardena, D., Klupinski, T. P., & Seay, B. (2022). Concentration profiles of per-and polyfluoroalkyl substances in major sources to the environment. *Journal of Environmental Management*, *301*, 113879. https://doi.org/10.1016/j.jenvman.2021.113879

Deng, S., Zhang, Q., Nie, Y., Wei, H., Wang, B., Huang, J., & Xing, B. (2012). Sorption mechanisms of perfluorinated compounds on carbon nanotubes. Environmental Pollution, 168, 138-144. doi:10.1016/j.envpol.2012.03.048.

Dixit, F., Dutta, R., Barbeau, B., Berube, P., & Mohseni, M. (2021). PFAS removal by ion exchange resins: A review. *Chemosphere*, *272*, 129777.DOI:10.1016/j.chemosphere.2021.129777

DNR. (2022). Environmental and Health Impacts of PFAS. Wisconsin Department of Natural Resources, Madison, WI 53707-7921. https://dnt.wiscosin.gov.

Dolai, S., Vanluchene, A., Stavárek, P., Dzik, P., Fajgar, R., Soukup, K., & Kluson̆, P. (2022). Graphitic carbon nitride thin films for light-induced photocatalysis in a slit geometry microreactor. *Journal of Environmental Chemical Engineering*, *10*(6), 108790. https://doi.org/10.1016/j.jece.2022.108790

Domingo, J. L., Ericson-Jogsten, I., Perello, G., Nadal, M., Van´ Bavel, B., & Karrman, A. (2012). Human exposure to perfluorinated compounds in Catalonia, Spain: contribution of drinking water and fish and shellfish. Journal of Agricultural and Food Chemistry, 60, 4408−4415. https://pubs.acs.org/doi/abs/10.1021/jf300355c

Duchesne, A. L., Brown, J., Patch, D., Major, D. W., Weber, K. P., & Gerhard, J. I. (2020). Remediation of PFAS-Contaminated Soil and Granular Activated Carbon by Smouldering Combustion. Environmental Science & Technology, 54(18), 11651-11661.

Dvorakova, D., Jurikova, M., Svobodova, V., Parizek, O., Kozisek, F., Kotal, F., Jeligova, H., Mayerova, L., & Pulkrabova, J. (2023). Complex monitoring of perfluoroalkyl substances (PFAS) from tap drinking water in the Czech Republic. *Water Research, 247*, 120764. https://doi.org/10.1016/j.watres.2023.120764

Eisenstein, O., Milani, J., & Perutz, R. N. (2017). Selectivity of C–H activation and competition between C–H and C–F bond activation at fluorocarbons. Chemical Reviews, 117(13), 8710-8753.

Emiliano, P., Katarina, B., Danijela, D. C., Djordjevic, A. B., & Saso, L. (2022). PFAS molecules: a major concern for the human health and the environment. *TOXICS*, *10*(2).

EPA. (2018). Fact sheet: Draft toxicity assessments for GenX chemicals and PFBS. https://www.epa.gov/sites/default/files/2018-11/documents/factsheet_pfbs-genx-toxicity_values_11.14.2018.pdf

Eze, C. T., Otitoloju, A. A., Eze, O. O., Ugochukwu, T. E., Onodugo, C., Ali, A. M., Lyche, J. L., Karlsen, O. A., & Goksøyr, A. (2023). West African e-waste-soil assessed with a battery of cell-based bioassays. *Science of The Total Environment, 856*(Part 1), 159068. https://doi.org/10.1016/j.scitotenv.2022.159068

Feng, K., Zhang, X., Wu, Z., Shi, Y., Su, M., Yang, K., Wang, Y., Sun, H., Min, J., Zhang, Y., Cheng, X., Woo, H. Y., & Guo, X. (2019). Fluorine-Substituted Dithienylbenzodiimide-Based n-Type Polymer Semiconductors for Organic Thin-Film Transistors. ACS Applied Materials & Interfaces, 11(39), 35924-35934. https://doi.org/10.1021/acsami.9b13138

Fenton, S. E., Ducatman, A., Boobis, A., DeWitt, J. C., Lau, C., Ng, C., & Roberts, S. M. (2021). Per-and polyfluoroalkyl substance toxicity and human health review: Current state of knowledge and strategies for informing future research. Environmental toxicology and chemistry, 40(3), 606-630. DOI: 10.1002/etc.4890.

Franke, V., Ullberg, M., McCleaf, P., Wålinder, M., Köhler, S. J., & Ahrens, L. (2021). *The Price of Really Clean Water: Combining Nanofiltration with Granular Activated Carbon and Anion Exchange Resins for the Removal of Per- And Polyfluoralkyl Substances (PFASs) in Drinking Water Production. ACS ES&T Water, 1(4), 782–795.* doi:10.1021/acsestwater.0c00141

Fredriksson, F., Eriksson, U., Kärrman, A., & Yeung, L. W. Y. (2022). Per- and polyfluoroalkyl substances (PFAS) in sludge from wastewater treatment plants in Sweden—First findings of novel fluorinated copolymers in Europe including temporal analysis. *Science of The Total Environment, 846*, 157406. https://doi.org/10.1016/j.scitotenv.2022.157406

Gaines, L. G. T. (2022). Historical and current usage of per- and polyfluoroalkyl substances (PFAS): A literature review. American Journal of Industrial Medicine. Advance online publication. https://doi.org/10.1002/ajim.23362

Gałęzowska, G., Rogowska, J., Olkowska, E., Ratajczyk, W., & Wolska, L. (2021). Environmental Risk Assessment Resulting from Sediment Contamination with Perfluoroalkyl Substances. *Molecules, 26*(1), 116. https://doi.org/10.3390/molecules26010116

Gallen, C., Drage, D., Eaglesham, G., Grant, S., Bowman, M., & Mueller, J. F. (2017). Australia-wide assessment of perfluoroalkyl substances (PFASs) in landfill leachates. Journal of hazardous materials, 331, 132-141. https://doi.org/10.1016/j.jhazmat.2017.02.006.

Gander, M. J. (2022). Climate change and the water quality threats posed by the emerging contaminants per-and polyfluoroalkyl substances (PFAS) and microplastics. *Water International*, 1-23. https://doi.org/10.1080/02508060.2022.2120255

Ganie, A. S., Bano, S., Khan, N., Sultana, S., Rehman, Z., Rahman, M. M., Sabir, S., Coulon, F., & Khan, M. Z. (2021). Nanoremediation technologies for sustainable remediation of contaminated environments: Recent advances and challenges. Chemosphere, 275, 130065. doi:10.1016/j.chemosphere.2021.130065

Garg, A., Shetti, N. P., Basu, S., Nadagouda, M. N., & Aminabhavi, T. M. (2023). Treatment technologies for removal of per- and polyfluoroalkyl substances (PFAS) in biosolids. *Chemical Engineering Journal, 453*(2), 139964. https://doi.org/10.1016/j.cej.2022.139964

Gebbink, W. A., & van Leeuwen, S. P. J. (2020). Environmental contamination and human exposure to PFASs near a fluorochemical production plant: Review of historic and current PFOA and GenX contamination in the Netherlands. *Environment International, 137*, 105583. https://doi.org/10.1016/j.envint.2020.105583

Glenn, G., Shogren, R., Jin, X., Orts, W., Hart-Cooper, W., & Olson, L. (2021). Per-and polyfluoroalkyl substances and their alternatives in paper food packaging. Comprehensive Reviews in Food Science and Food Safety, 20(3), 2596-2625. https://doi.org/10.1111/1541-4337.12726

Glüge, J., Scheringer, M., Cousins, I. T., DeWitt, J. C., Goldenman, G., Herzke, D., Lohmann, R., Ng, C. A., Trier, X., & Wang, Z. (2020). An overview of the uses of per- and polyfluoroalkyl substances (PFAS). Environmental Science: Processes & Impacts, 22(12), 2345-2373. https://doi.org/10.1039/D0EM00291G

Groffen, T., Nkuba, B., Wepener, V., & Bervoets, L. (2021). Risks posed by per-and polyfluoroalkyl substances (PFAS) on the African continent, emphasizing aquatic ecosystems. Integrated Environmental Assessment and Management, 17(4), 726-732.

Groffen, T., Wepener, V., Malherbe, W., & Bervoets, L. (2018). Distribution of perfluorinated compounds (PFASs) in the aquatic environment of the industrially polluted Vaal River, South Africa. Science of the Total Environment, 627, 1334-1344.

Guillette, T. C., McCord, J., Guillette, M., Polera, M. E., Rachels, K. T., Morgeson, C., & Belcher, S. M. (2020). Elevated levels of per-and polyfluoroalkyl substances in Cape Fear River Striped Bass (Morone saxatilis) are associated with biomarkers of altered immune and liver function. Environment international, 136, 105358.

Halonen, J. I., Erhola, M., Furman, E., Haahtela, T., Jousilahti, P., Barouki, R., & Antó, J. M. (2021). Discussion: A call for urgent action to safeguard our planet and our health in line with the Helsinki Declaration. Environmental Research, 193, 110600. https://doi.org/10.1016/j.envres.2020.110600

Hannah, T. H. A. B. E. T. (2022). Per-and Polyfluoroalkyl Substances and Alternatives in Coatings, Paints and Varnishes (CPVs). Report on the Commercial Availability and Current Uses. Series on Risk Management No. 70. https://www.oecd.org/chemicalsafety/portal-perfluorinated-chemicals/per-and-polyfluoroalkyl-substances-alternatives-in-coatings-paints-varnishes.pdf.

Haron, D. E. M., Yoneda, M., Hod, R., Wahab, M. I. A., & Aziz, M. Y. (2022). Perfluoroalkyl and polyfluoroalkyl substances, bisphenol and paraben compounds in dust collected from residential homes in Klang Valley, Malaysia. *Human and Ecological Risk Assessment: An International Journal, 28*(8), 827-843. https://doi.org/10.1080/10807039.2022.2101429

Harris, M. A., Oken, E., Rifas-Shiman. S. L., Calafat. A. M., Bellinger. D.C., & Sagiv. S.K. (2021). Prenatal and childhood exposure to per- and polyfluoroakyl substnaces (PFAS) and child executive function and behavioral problems. Journal of Environmental Research, 202 https://doi.org/10.1016/j.envres.2021.111621.

He, A., Lu, Y., Chen, F., Li, F., Lv, K., Cao, H., Sun, Y., Liang, Y., Li, J., Zhao, L., Zhang, X., Li. L., Wang., Y., & Jiang, G. (2022). Exploring the origin of efficient adsorption of poly-and perfluoroalkyl substances in household point-of-use water purifiers: Deep insights from a joint experimental and computational study. *Science of The Total Environment*, *831*, 154988. https://doi.org/10.1016/j.scitotenv.2022.154988

Heo, J. J., Lee, J. W., Kim, S. K., & Oh, J. E. (2014). Foodstuff analyses show that seafood and water are major perfluoroalkyl acids (PFAAs) sources to humans in Korea. Journal of Hazardous Materials, 279, 402-409. https://doi.org/10.1016/j.jhazmat.2014.07.004

Hlouskova, V., Hradkova, P., Poustka, J., Brambilla, G., De Filipps, S. P., D'Hollander, W., Bervoets, L., Herzke, D., Huber, S., de Voogt, P., & Pulkrabova, J. (2013). Occurrence of perfluoroalkyl substances (PFASs) in various food items of animal origin collected in four European countries. Food Additives & Contaminants: Part A, 30(11), 1918-1932. https://doi.org/10.1080/19440049.2013.837585

Hunter, L. (2010). The C–F bond as a conformational tool in organic and biological chemistry. Beilstein journal of organic chemistry, 6(1), 38.

Ibor, O. R., Andem, A. B., Eni, G., Arong, G. A., Adeougn, A. O., & Arukwe, A. (2020). Contaminant levels and endocrine disruptive effects in Clarias gariepinus exposed to simulated leachate from a solid waste dumpsite in Calabar, Nigeria. *Aquatic toxicology*, *219*, 105375. https://doi.org/10.1016/j.aquatox.2019.105375

Ismaeili, J., Patel, J., & Övez, B. (2022). The Conceptual Study of Non-Stick Cookware Coatings and the Effect of Some Corresponding Additives on Their Performance. *Scientific Research Communications*, *2*(2). https://doi.org/10.52460/src.2022.007

ITRC (Interstate Technology & Regulatory Council). (2022). *PFAS Technical and Regulatory Guidance Document and Fact Sheets* PFAS-1. Washington, D.C.: Interstate Technology & Regulatory Council, PFAS Team. https://pfas-1.itrcweb.org/.

Järnberg, U., Holmström, K., van Bavel, B., & Kärrman, A. (2007). Perfluoroalkylated acids and related compounds (PFAS) in the Swedish environment.

Ji, B., Kang, P., Wei, T., & Zhao, Y. (2020). Challenges of aqueous per- and polyfluoroalkyl substances (PFAS) and their foreseeable removal strategies. Chemosphere, 250, 126316.

Jin, R., McConnell, R., Catherine, C., Xu, S., Walker, D. I., Stratakis, N., & Chatzi, L. (2020). Perfluoroalkyl substances and severity of nonalcoholic fatty liver in children: an untargeted metabolomics approach. Environment international, 134, 105220.

Johansson, J. (2017). Sources, transport and fate of perfluoroalkyl acids in the atmosphere (Doctoral dissertation, Department of Environmental Science and Analytical Chemistry, Stockholm University).

Kalra, S. S., Cranmer, B., Dooley, G., Hanson, A. J., Maraviov, S., Mohanty, S. K., Blotevogel, J., & Mahendra,

S. (2021). Sonolytic destruction of Per- and polyfluoroalkyl substances in groundwater, aqueous Film-Forming Foams, and investigation derived waste. *Chemical Engineering Journal, 425*, 131778. https://doi.org/10.1016/j.cej.2021.131778

Kanchanapiya, P., &Tantisattayakul, T. (2022). Analysis of the additional cost of addressing per-and polyfluoroalkyl substance contamination from landfill leachate by reverse osmosis membranes in Thailand. *Journal of Water Process Engineering*, *45*, 102520.https://doi.org/10.1016/j.jwpe.2021.102520

Karidis, A. (2022). New PFAS Remediation Technology Comes to U.S. Waste360. Retrieved from https://www.waste360.com/pfas-pfoas/new-pfas-remediation-technology-comes-us

Kayode, O. F., Luethi, C., & Rene, E. R. (2018). Management Recommendations for Improving Decentralized Wastewater Treatment by the Food and Beverage Industries in Nigeria. *Environments* 5, no. 3: 41. https://doi.org/10.3390/environments5030041

Kewalramani, J. A., Wang, B., Marsh, R. W., Meegoda, J. N., & Freire, L. R. (2022). Coupled high and low-frequency ultrasound remediation of PFAS-contaminated soils. Ultrasonics Sonochemistry, 88, 106063.

Kotthoff, M., Fliedner, A., Rüdel, H., Göckener, B., Bücking, M., Biegel-Engler, A., & Koschorreck, J. (2020). Per- and polyfluoroalkyl substances in the German environment – Levels and patterns in different matrices. *Science of The Total Environment, 740*, 140116. https://doi.org/10.1016/j.scitotenv.2020.140116

Krause, M. J., Thoma, E., Sahle-Damesessie, E., Crone, B., Whitehill, A., Shields, E., & Gullett, B. (2022). Supercritical water oxidation as an innovative technology for PFAS destruction. *Journal of Environmental Engineering*, *148*(2), 05021006. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001957

Kucharzyk, K. H., Darlington, R., Benotti, M., Deeb, R., & Hawley, E. (2017). Novel treatment technologies for PFAS compounds: A critical review. Journal of Environmental Management, 1-8.

Kulkarni, P. R., Richardson, S. D., Nzeribe, B. N., Adamson, D. T., Kalra, S. S., Mahendra, S., Blotevogel, J., Hanson, A., Dooley, G., Maraviov, S., and Popovic, J. (2022). Field Demonstration of a Sonolysis Reactor for Treatment of PFAS-Contaminated Groundwater. *Journal of Environmental Engineering*, *148*(11), 06022005. https://doi.org/10.1061/(ASCE)EE.1943-7870.0002064

Kurwadkar, S., Dane, J., Kanel, S. R., Nadagouda, M. N., Cawdrey, R. W., Ambade, B., Struckhoff, G. C., & Wilkin, R. (2022). Per- and polyfluoroalkyl substances in water and wastewater: A critical review of their global occurrence and distribution. Science of The Total Environment, 809, 151003. https://doi.org/10.1016/j.scitotenv.2021.151003.

Lee, Y.-M., Lee, J.-Y., Kim, M.-K., Yang, H., Lee, J.-E., Son, Y., Kho, Y., Choi, K., & Zoh, K.-D. (2020). Concentration and distribution of per- and polyfluoroalkyl substances (PFAS) in the Asan Lake area of South Korea. Journal of Hazardous Materials, 381, 120909. https://doi.org/10.1016/j.jhazmat.2019.120909

Lenka, S. P., Kah, M., & Padhye, L. P. (2022). Occurrence and fate of poly- and perfluoroalkyl substances (PFAS) in urban waters of New Zealand. *Journal of Hazardous Materials, 428*, 128257. https://doi.org/10.1016/j.jhazmat.2022.128257

Lenka, S. P., Kah, M., & Padhye, L. P. (2022). Occurrence and fate of poly- and perfluoroalkyl substances (PFAS) in urban waters of New Zealand. Journal of Hazardous Materials, 428, 128257. https://doi.org/10.1016/j.jhazmat.2022.128257

Leung, S. C. E., Shukla, P., Chen, D., Eftekhari, E., An, H., Zare, F., Ghasemi, N., Zhang, D., Nguyen, N. T., & Li, Q. (2022). Emerging technologies for PFOS/PFOA degradation and removal: A review. Science of The Total Environment, 827, 153669. https://doi.org/10.1016/j.scitotenv.2022.153669

Lewis, A. J., Yun, X., Spooner, D. E., Kurz, M. J., McKenzie, E. R., & Sales, C. M. (2022). Exposure pathways and bioaccumulation of per-and polyfluoroalkyl substances in freshwater aquatic ecosystems: Key considerations. Science of The Total Environment, 153561. https://doi.org/10.1016/j.scitotenv.2022.153561

Li, C., Zhong, H., Wu, J., Meng, L., Wang, Y., Liao, C., & He, Y. (2024). Migration mechanism and risk assessment of per- and polyfluoroalkyl substances in the Ya'Er Lake oxidation pond area, China. Journal of Environmental Sciences, 136, 301-312. https://doi.org/10.1016/j.jes.2022.12.008

Li, F., Duan, J., Tian, S., Ji, H., Zhu, Y., Wei, Z., & Zhao, D. (2019). *Short-chain Per- and Polyfluoroalkyl Substances in Aquatic Systems: Occurrence, Impacts and Treatment. Chemical Engineering Journal, 122506.* doi:10.1016/j.cej.2019.122506

Li, F., Duan, J., Tian, S., Ji, H., Zhu, Y., Wei, Z., & Zhao, D. (2020). Short-chain per-and polyfluoroalkyl substances in aquatic systems: Occurrence, impacts and treatment. Chemical Engineering Journal, 380, 122506. https://doi.org/10.1016/j.cej.2019.122506.

Li, J., Austin, C., Moore, S., Pinkard, B. R., & Novosselov, I. V. (2023). PFOS destruction in a continuous supercritical water oxidation reactor. *Chemical Engineering Journal, 451*(4), 139063. https://doi.org/10.1016/j.cej.2022.139063

Li, X., Fatowe, M., Lemos, L., & Quinete, N. (2022). Spatial distribution of per- and polyfluoroalkyl substances (PFAS) in waters from Central and South Florida. Environmental Science and Pollution Research, 29, 84383-84395.

Li. Y., Barregard. L., Xu. Y., Scott. K., Pineda. D., Lindh. C., & Fletcher. T. (2020). Associations between perfluoroalkyl substances and serum lipids in a Swedish adult population with contaminated drinking water. Journal of Environmental Health, 19: 33.

Lin, H., Taniyasu, S., Yamazaki, E., Wei, S., Wang, X., Gai, N., & Yamashita, N. (2020). Per-and polyfluoroalkyl substances in the air particles of Asia: levels, seasonality, and size-dependent distribution. Environmental Science & Technology, 54(22), 14182-14191. https://doi.org/10.1021/acs.est.0c03387.

Lin, P. I. D., Cardenas, A., Hauser, R., Gold, D. R., Kleinman, K. P., Hivert, M. F., & Oken, E. (2019). Per-and polyfluoroalkyl substances and blood lipid levels in pre-diabetic adults—longitudinal analysis of the diabetes prevention program outcomes study. Environment international, 129, 343-353.

Liu, X., Guo, X., Liu, Y., Lu, S., Xi, B., Zhang, J., Wang, Z., & Bi, B. (2019). A review on removing antibiotics and antibiotic resistance genes from wastewater by constructed wetlands: Performance and microbial response. Environmental Pollution, 254(Part A), 112996. https://doi.org/10.1016/j.envpol.2019.112996

Liu, Z., Xu, C., Johnson, A. C., Sun, X., Ding, X., Ding, D., Liu, S., & Liang, X. (2022). Source apportionment and crop bioaccumulation of perfluoroalkyl acids and novel alternatives in an industrial-intensive region with fluorochemical production, China: Health implications for human exposure. Journal of Hazardous Materials, 423(Part A), 127019. https://doi.org/10.1016/j.jhazmat.2021.127019

Lohmann, R., Cousins, I. T., DeWitt, J. C., Glüge, J., Goldenman, G., Herzke, D., Lindstrom, A. B., Miller, M. F., Ng, C. A., Patton, S., Scheringer, M., Trier, X., & Wang, Z. (2020). Are fluoropolymers really of low concern for human and environmental health and separate from other PFAS? Environmental Science & Technology, 54(20), 12820-12828. https://doi.org/10.1021/acs.est.0c03244.

Longendyke, G. K., Katel, S., & Wang, Y. (2022). PFAS fate and destruction mechanisms during thermal treatment: a comprehensive review. *Environmental Science: Processes & Impacts*, *24*(2), 196-208. DOI: https://doi.org/10.1039/D1EM00465D

Lu, D., Sha, S., Luo, J., Huang, Z., & Jackie, X. Z. (2020). Treatment train approaches for the remediation of per- and polyfluoroalkyl substances (PFAS): A critical review. *Journal of hazardous materials*, *386*, 121963. https://doi.org/10.1016/j.jhazmat.2019.121963

Lyu, X., Xiao, F., Shen, C., Chen, J., Park, C. M., Sun, Y., & Wang, D. (2022). Per-and Polyfluoroalkyl Substances (PFAS) in Subsurface Environments: Occurrence, Fate, Transport, and Research Prospect. Reviews of Geophysics, 60(3), e2021RG000765. https://doi.org/10.1029/2021RG000765.

Ma, D., Zhong, H., Lv, J., Wang, Y., & Jiang, G. (2022). Levels, distributions, and sources of legacy and novel per- and perfluoroalkyl substances (PFAS) in the topsoil of Tianjin, China. Journal of Environmental Sciences, 112, 71-81. https://doi.org/10.1016/j.jes.2021.04.029

Macheka, L. R., Olowoyo, J. O., Mugivhisa, L. L., & Abafe, O. A. (2021). Determination and assessment of human dietary intake of per and polyfluoroalkyl substances in retail dairy milk and infant formula from South Africa. *Science of The Total Environment*, 755(Part 2), 142697. https://doi.org/10.1016/j.scitotenv.2020.142697

Mahinroosta R, & Senevirathna L. (2020). A review of the emerging treatment technologies for PFAS contaminated soils. J Environ Manage. 1;255:109896. doi: 10.1016/j.jenvman.2019.109896.

Masoner, J. R., Kolpin, D. W., Cozzarelli, I. M., Smalling, K. L., Bolyard, S. C., Field, J. A., & Bradley, P. M. (2020). Landfill leachate contributes per-/poly-fluoroalkyl substances (PFAS) and pharmaceuticals to municipal wastewater. *Environmental Science: Water Research & Technology*, *6*(5), 1300-1311. 10.1039/D0EW00045K

McCleaf, P., Englund, S., Östlund, A., Lindegren, K., Wiberg, K., & Ahrens, L. (2017). Removal efficiency of multiple poly- and perfluoroalkyl substances (PFASs) in drinking water using granular activated carbon (GAC) and anion exchange (AE) column tests. *Water Research, 120, 77–87.* doi:10.1016/j.watres.2017.04.057

McDermett, K., Anderson, T., Jackson, W. A., & Guelfo, J. (2022). Assessing Potential Perfluoroalkyl Substances Trophic Transfer to Crickets (Acheta domesticus). Environmental Toxicology and Chemistry. 41(12):2981-2992. doi: 10.1002/etc.5478.

McDonough, J. T., Kirby, J., Bellona, C., Quinnan, J. A., Welty, N., Follin, J., & Liberty, K. (2022). Validation of supercritical water oxidation to destroy perfluoroalkyl acids. *Remediation Journal*, *32*(1-2), 75-90. **https://doi.org/10.1002/rem.21711**

McGregor, R. (2018). In situ treatment of PFAS-impacted groundwater using colloidal activated carbon. *Remediation Journal*, *28*(3), 33-41. **https://doi.org/10.1002/rem.21558**

Meegoda, J. N., Kewalramani, J. A., Li, B., & Marsh, R. W. (2020). A Review of the Applications, Environmental Release, and Remediation Technologies of Per- and Polyfluoroalkyl Substances. *International journal of environmental research and public health*, *17*(21), 8117. https://doi.org/10.3390/ijerph17218117

Milinovic, J., Lacorte, S., Vidal, M., & Rigol, A. (2015). Sorption behaviour of perfluoroalkyl substances in soils. *Science of the Total Environment*, *511*, 63-71. https://doi.org/10.1016/j.scitotenv.2014.12.017

Militao, I. M., Roddick, F., Bergamasco, R., & Fan, L. (2022). Rapid adsorption of PFAS: Application of Moringa oleifera seed powder encapsulated in alginate beads. Environmental Technology & Innovation, 28, 102761.

Mirabediny, M., Sun, J., Yu, T.T., Åkermark, B., Das, B., & Kumar, N. (2023). Effective PFAS degradation by electrochemical oxidation methods-recent progress and requirement. Chemosphere, 321, 138109. https://doi.org/10.1016/j.chemosphere.2023.138109

Munoz, G., Mercier, L., Vo Duy, S., Liu, J., Sauvé, S., & Houde, M. (2022). Bioaccumulation and trophic magnification of emerging and legacy per- and polyfluoroalkyl substances (PFAS) in a St. Lawrence River food web. Environmental Pollution, 309, 119739. https://doi.org/10.1016/j.envpol.2022.119739

Munson, A. (2023). Cost Implications of PFAS Destruction in Biosolids: A Case Study from the Minnesota Pollution Control Agency. In *Residuals and Biosolids 2023*. Water Environment Federation. DOI: 10.2175/193864718825158810

Nadagouda, M. N., & Lee, T. (2021). Cross-Flow Treatment of PFAS in Water: Materials Challenges and Potential Solutions. Accounts of Materials Research, 2(3), 129-133. https://doi.org/10.1021/accountsmr.0c00106

Nascimento, R. A., Nunoo, D. B. O., Bizkarguenaga, E., Schultes, L., Zabaleta, I., Benskin, J. P., Spanó, S., & Leonel, J. (2018). Sulfluramid use in Brazilian agriculture: A source of per- and polyfluoroalkyl substances (PFASs) to the environment. *Environmental Pollution, 242*(B), 1436-1443. https://doi.org/10.1016/j.envpol.2018.07.122

Nguyen, H. T., McLachlan, M. S., Tscharke, B., Thai, P., Braeunig, J., Kaserzon, S., O'Brien, J. W., & Mueller, J. F. (2022). Background release and potential point sources of per- and polyfluoroalkyl substances to municipal wastewater treatment plants across Australia. Chemosphere, 293, 133657. https://doi.org/10.1016/j.chemosphere.2022.133657

Nguyen, K. L. (2023). Determination of per-and polyfluorinated alkyl substances (PFAS) in municipal wastewater in Vietnam. https://urn.fi/URN:NBN:fi-fe2023080493091

Nguyen, T. M. H., Bräunig, J., Thompson, K., Thompson, J., Kabiri, S., Navarro, D. A., & Mueller, J. F. (2020). Influences of chemical properties, soil properties, and solution pH on soil–water partitioning coefficients of per-and polyfluoroalkyl substances (PFASs). Environmental science & technology, 54(24), 15883-15892. https://doi.org/10.1021/acs.est.0c05705.

Olsavsky, N. J., Kearns, V. M., Beckman, C. P., Sheehan, P. L., Burpo, F. J., Bahaghighat, H. D., & Nagelli, E. A. (2020). Research and Regulatory Advancements on Remediation and Degradation of Fluorinated Polymer Compounds. Applied Sciences, 10(19), 6921.

Olufsen, M., & Arukwe, A. (2015). Endocrine, biotransformation, and oxidative stress responses in salmon hepatocytes exposed to chemically induced hypoxia and perfluorooctane sulfonamide (PFOSA), given singly or in combination. Environmental Science and Pollution Research, 22(22), 17350-17366.

Olvera-Vargas, H., Wang, Z., Xu, J., & Lefebvre, O. (2022). Synergistic degradation of GenX (hexafluoropropylene oxide dimer acid) by pairing graphene-coated Ni-foam and boron doped diamond electrodes. *Chemical Engineering Journal*, 430 (Part 1), 132686. https://doi.org/10.1016/j.cej.2021.132686

Onu, M. A., Ayeleru, O. O., Oboirien, B., & Olubambi, P. A. (2023). Challenges of wastewater generation and management in sub-Saharan Africa: A Review. Environmental Challenges, 11, 100686. https://doi.org/10.1016/j.envc.2023.100686

Pan, Y., Zhang, H., Cui, Q., Sheng, N., Yeung, L. W. Y., Sun, Y., Guo, Y., & Dai, J. (2018). Worldwide Distribution of Novel Perfluoroether Carboxylic and Sulfonic Acids in Surface Water. Environmental Science & Technology, 52(14), 7621-7629. https://doi.org/10.1021/acs.est.8b00829

Panieri, E., Baralic, K., Djukic-Cosic, D., Buha Djordjevic, A., & Saso, L. (2022). PFAS Molecules: A Major Concern for the Human Health and the Environment. Toxics, 10(2), 44. https://doi.org/10.3390/toxics10020044.

Pérez,F., Nadal,M., Navarro-ortega,A., Fabrega,F., Domingo,J.L., Barcelona,D., & Farr,M. (2013). Accumulation of perfluoroalkyl substances in human tissues. Environment International, 59,354-362. https://doi.org/10.1016/j.envint.2013.06.004.

Pétré, M.-A., Salk, K.R., Stapleton, H.M., Ferguson, P.L., Tait, G., Obenour, D.R., Knappe, D.R.U., & Genereux, D.P. (2022). Per- and polyfluoroalkyl substances (PFAS) in river discharge: Modeling loads upstream and downstream of a PFAS manufacturing plant in the Cape Fear watershed, North Carolina. Science of The Total Environment, 831, 154763. https://doi.org/10.1016/j.scitotenv.2022.154763

Pickard, H. M., Ruyle, B. J., Thackray, C. P., Chovancova, A., Dassuncao, C., Becanova, J., & Sunderland, E. M. (2022). PFAS and Precursor Bioaccumulation in Freshwater Recreational Fish: Implications for Fish Advisories. Environmental Science & Technology, 56(22), 15573-15583. doi: 10.1021/acs.est.2c03734.

Pizzurro,D.M., Seeley,M., Keeper,L.E., & Beck,B.D. (2019). Imterspecies differences in perfluoroalkyl substances (PFAS) toxicokinetics and application to health-based criteria. Regulatory toxicology and pharmacology, RTP, 106,239-250. https://doi.org/10.1016/jyrtph.2019.05.008.

Preston, E. V., Rifas-Shiman, S. L., Hivert, M. F., Zota, A. R., Sagiv, S. K., Calafat, A. M., & James-Todd, T. (2020). Associations of per-and polyfluoroalkyl substances (PFAS) with glucose tolerance during pregnancy in Project Viva. The Journal of Clinical Endocrinology & Metabolism, 105(8), e2864-e2876.

Qi, Y., Cao, H., Pan, W., Wang, C., & Liang, Y. (2022). The role of dissolved organic matter during Per-and Polyfluorinated Substance (PFAS) adsorption, degradation, and plant uptake: A review. Journal of Hazardous Materials, 129139. https://doi.org/10.1016/j.jhazmat.2022.129139.

Qin, W. P., Cao, L. Y., Li, C. H., Guo, L. H., Colbourne, J., & Ren, X. M. (2020). Perfluoroalkyl substances stimulate insulin secretion by islet β cells via G protein-coupled receptor 40. Environmental science & technology, 54(6), 3428-3436.

Quiñones, O., & Snyder, S. A. (2009). Occurrence of perfluoroalkyl carboxylates and sulfonates in drinking water utilities and related waters from the United States. Environmental science & technology, 43(24), 9089-9095. https://doi.org/10.1021/es9024707.

Ramos, P., Kalra, S. S., Johnson, N. W., Khor, C. M., Borthakur, A., Cranmer, B., Dooley, G., Mohanty, S. K., Jassby, D., Blotevogel, J., & Mahendra, S. (2022). Enhanced removal of per- and polyfluoroalkyl substances in complex matrices by polyDADMAC-coated regenerable granular activated carbon. Environmental Pollution, 294, 118603. https://doi.org/10.1016/j.envpol.2021.118603

Riegel, M., Haist-Gulde, B., & Sacher, F. (2023). Sorptive removal of short-chain perfluoroalkyl substances (PFAS) during drinking water treatment using activated carbon and anion exchanger. Environmental Sciences Europe, 35(1), 12. https://doi.org/10.1186/s12302-023-00716-5

Rodowa, A. E., Knappe, D. R., Chiang, S. Y. D., Pohlmann, D., Varley, C., Bodour, A., & Field, J. A. (2020). Pilot scale removal of per-and polyfluoroalkyl substances and precursors from AFFF-impacted groundwater by granular activated carbon. Environmental Science: Water Research & Technology, 6(4), 1083-1094.https://doi.org/10.1039/C9EW00936A

Rodríguez-Varela, M., Durán-Álvarez, J. C., Jiménez-Cisneros, B., Zamora, O., & Prado, B. (2021). Occurrence of perfluorinated carboxylic acids in Mexico City's wastewater: A monitoring study in the sewerage and a mega wastewater treatment plant. Science of The Total Environment, 774, 145060. https://doi.org/10.1016/j.scitotenv.2021.145060

Ross, I., McDonough, J., Miles, J., Storch, P., Kochunarayanan, P. T., Kalve, E., Hurst, J., Dasgupta, S. S., & Burdick, J. (2018). A review of emerging technologies for remediation of PFASs. Remediation Journal, 28(2), 81-92. https://doi.org/10.1002/rem.21553

Rylott, E. L., & Bruce, N. C. (2020). How synthetic biology can help bioremediation. Curr. Opin. Chem. Biol. 58, 86–95.

Salvatore, D., Mok, K., Garrett, K. K., Poudrier, G., Brown, P., Birnbaum, L. S., Goldenman, G., Miller, M. F., Patton, S., Poehlein, M., Varshavsky, J., & Cordner, A. (2022). Presumptive Contamination: A New Approach to PFAS Contamination Based on Likely Sources. Environmental Science & Technology Letters, 9(11), 983–990. https://doi.org/10.1021/acs.estlett.2c00502

Santiago, R. A., Medina, P. B., & Su, X. (2022). Electrochemical remediation of perfluoroalkyl substances from water. Electrochimica Acta, 403, 139635. doi:10.1016/j.electacta.2021.139635

Sarkar, B., Mukhopadhyay, R., Ramanayaka, S., Bolan, N., & Ok, Y. S. (2021). The role of soils in the disposition, sequestration and decontamination of environmental contaminants. *Philosophical Transactions of the Royal Society B*, *376*(1834), 20200177. **https://doi.org/10.1098/rstb.2020.0177**

Savoca, D., & Pace, A. (2021). Bioaccumulation, Biodistribution, Toxicology and Biomonitoring of Organofluorine Compounds in Aquatic Organisms. International Journal of Molecular Sciences, 22(12), 6276. https://doi.org/10.3390/ijms22126276

Schedin, E. (2013). Effect of Organic Carbon, Active Carbon, Calcium Ions and Aging on the Sorption of Per- and Polyfluoroalkylated Substances (PFASs) to Soil. pp. 75.

Schellenberger, S., Gillgard, P., Stare, A., Hanning, A., Levenstam, O., Roos, S., & Cousins, I. T. (2018). Facing the rain after the phase out: Performance evaluation of alternative fluorinated and non-fluorinated durable water repellents for outdoor fabrics. Chemosphere, 193, 675-684. https://doi.org/10.1016/j.chemosphere.2017.11.027.

Shahsavari, E., Rouch, D., Khudur, L. S., Thomas, D., Aburto-Medina, A., & Ball, A. S. (2021). Challenges and Current Status of the Biological Treatment of PFAS-Contaminated Soils. *Frontiers in bioengineering and biotechnology*, *8*, 602040. https://doi.org/10.3389/fbioe.2020.602040

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

Sharma, S., Shetti, N. P., Basu, S., Nadagouda, M. N., & Aminabhavi, T. M. (2022). Remediation of per- and polyfluoroalkyls (PFAS) via electrochemical methods. Chemical Engineering Journal, 430(2), 132895. https://doi.org/10.1016/j.cej.2021.132895

Shi, X., & Zhou, B. (2010). The role of Nrf2 and MAPK pathways in PFOS-induced oxidative stress in zebrafish embryos. Toxicological Sciences, 115(2), 391-400.

Shimizu, M., Fujii, S., Tanaka, T., & Kataura, H. (2013). Effects of surfactants on the electronic transport properties of thin-film transistors of single-wall carbon nanotubes. *The Journal of Physical Chemistry C*, *117*(22), 11744-11749. DOI:10.1021/jp3113254.

Sindiku O., Orata F., Haglund P., Tysklind M., Weber R., & Osibanjo O. (2014). PCDD/F and Per- & Polyfluoroalkyl Substances Contamination in Selected Sewage Sludges in Nigeria. Organohalogen Compounds. Vol. 76, 368-371.

Sindiku, O., Orata, F., Weber, R., & Osibanjo, O. (2013). Per- and polyfluoroalkyl substances in selected sewage sludge in Nigeria. Chemosphere, 92(3), 329–335. doi:10.1016/j.chemosphere.2013.04.010.

Smith, S. J., Lauria, M., Ahrens, L., McCleaf, P., Hollman, P., Bjälkefur Seroka, S., Hamers, T., Arp, H. P. H., &Wiberg, K. (2023). Electrochemical Oxidation for Treatment of PFAS in Contaminated Water and Fractionated Foam-A Pilot-Scale Study. *ACS ES&T water*, *3*(4), 1201–1211. https://doi.org/10.1021/acsestwater.2c00660

Stahl, T., Mattern, D. & Brunn, H. Toxicology of perfluorinated compounds. *Environ Sci Eur* **23**, 38 (2011). https://doi.org/10.1186/2190-4715-23-38.

Stefano, P. H. P., Roisenberg, A., Acayaba, R. D., Roque, A. P., Bandoria, D. R., Soares, A., & Montagner, C. C. (2023). Occurrence and distribution of per-and polyfluoroalkyl substances (PFAS) in surface and groundwaters in an urbanized and agricultural area, Southern Brazil. Environmental Science and Pollution Research, 30, 6159-6169. doi:10.1007/s11356-022-2195-9

Sun, H., Zhang, X., Wang, L., Zhang, T., Li, F., He, N., & Alder, A. C. (2012). Perfluoroalkyl compounds in municipal WWTPs in Tianjin, China—concentrations, distribution and mass flow. Environmental Science and Pollution Research, 19(5), 1405-1415. https://doi.org/10.1007/s11356-011-0727-6.

Sun, J., Jennepalli, S., Lee, M., O'Carroll, D. M., Akermark, B., Manefield, M. J., Das, B., & Kumar, N. (2021). Removal of per- and polyfluoroalkyl substances (PFAS) from water by ceric(IV) ammonium nitrate. RSC Advances, 11(30), 17642-17652.

Tansel, B. (2022). PFAS use in electronic products and exposure risks during handling and processing of e-waste: A review. Journal of Environmental Management, 316, 115291. https://doi.org/10.1016/j.jenvman.2022.115291

Thepakson, P., Lee, P., Shiwaku, Y., Zheng, B., Koizumi, A., Harada, K. (2022). Formation and Degradability of Per- and PolyuoroalkylSubstances in River Soils around a FluoropolymerManufacturing Plant in Osaka, Japan. *Research Square*. 10.21203/rs.3.rs-2241593/v1

Toms, L. M. L., Bräunig, J., Vijayasarathy, S., Phillips, S., Hobson, P., Aylward, L. L., & Mueller, J. F. (2019). Per-and polyfluoroalkyl substances (PFAS) in Australia: current levels and estimated population reference values for selected compounds. International Journal of Hygiene and Environmental Health, 222(3), 387-394. https://doi.org/10.1016/j.ijheh.2019.03.004.

Tow, E. W., Ersan, M. S., Kum, S., Lee, T., Speth, T. F., Owen, C., Bellona, C., Nadagouda, M. N., Mikelonis, A. M., Westerhoff, P., Mysore, C., Frenkel, V. S., de Silva, V., Walker, W. S., Safulko, A. K., & Ladner, D. A. (2021). Managing and treating per- and polyfluoroalkyl substances (PFAS) in membrane concentrates. AWWA Water Science, 3(5), e1233.

Tudi, M., Daniel Ruan, H., Wang, L., Lyu, J., Sadler, R., Connell, D., Chu, C., & Phung, D. T. (2021). Agriculture Development, Pesticide Application and Its Impact on the Environment. *International journal of environmental research and public health*, *18*(3), 1112. https://doi.org/10.3390/ijerph18031112.

USEPA. (2022a). PFAS Explained. United States Environmental Protection Agency. https:// www.epa.gov/pfas/pfas-explained

USEPA. (2022b). Our Current Understanding of the Human Health and Environmental Risks of PFAS. https:/www.epa.gov/pfas/our-current-understanding-of-the-human-helath and-

Van Der Veen, H., & Kapadia, M. G. (2021). Transitioning To a Circular Economy Through Chemical and Waste Management. https://www.undp.org/sites/g/files/zskgke326/files/2022-03/UNDP-GEF-Transitioning-to-a-Circular-Economy-Through-Chemical-and-Waste-Management.pdf.

Vendl, C., Taylor, M. D., Bräunig, J., Gibson, M. J., Hesselson, D., Neely, G. G., & Nakagawa, S. (2021). Profiling research on PFAS in wildlife: Protocol of a systematic evidence map and bibliometric analysis. *Ecological Solutions and Evidence*, *2*(4), e12106. https://doi.org/10.1002/2688-8319.12106

Verma,S., Varma, R.S., & Nadagouda, M. N. Remediation and mineralization processes for per- and polyfluoroalkyl substances (PFAS) in water: A review. Science of the Total Environment 794 (2021) 148987.

Vo, H. N. P., Ngo, H. H., Guo, W., Nguyen, T. M. H., Li, J., Liang, H., & Nguyen, T. A. H. (2020). Poly-and perfluoroalkyl substances in water and wastewater: a comprehensive review from sources to remediation. *Journal of Water Process Engineering*, *36*, 101393. https://doi.org/10.1016/j.jwpe.2020.101393.

Vu, C. T., & Wu, T. (2022). Recent progress in adsorptive removal of per-and poly-fluoroalkyl substances (PFAS) from water/wastewater. *Critical Reviews in Environmental Science and Technology*, *52*(1), 90-129.

https://doi.org/10.1080/10643389.2020.1816125

Wang, H., Wang, T., Zhang, B., Li, F., Toure, B., Omosa, I. B., & Pradhan, M. (2013). Water and Wastewater Treatment in Africa - Current Practices and Challenges. CLEAN - Soil, Air, Water, 42(8), 1029–1035. doi:10.1002/clen.201300208

Wang, P., Liu, D., Yan, S., Cui, J., Liang, Y., & Ren, S. (2022). Adverse Effects of Perfluorooctane Sulfonate on the Liver and Relevant Mechanisms. Toxics, 10(5), 265. doi: 10.3390/toxics10050265.

Wang, Y. Q., Hu, L. X., Liu, T., Zhao, J. H., Yang, Y. Y., Liu, Y. S., & Ying, G. G. (2022). Per-and polyfluoralkyl substances (PFAS) in drinking water system: Target and non-target screening and removal assessment. Environment International, 163, 107219. https://doi.org/10.1016/j.envint.2022.107219

Wang, Y., Starling, A. P., Haug, L. S., Eggesbo, M., Becher, G., Thomsen, C., & Longnecker, M. P. (2013). Association between perfluoroalkyl substances and thyroid stimulating hormone among pregnant women: a cross-sectional study. Environmental Health, 12(1), 1-7.

Wanninayake, D. M. (2021). Comparison of currently available PFAS remediation technologies in water: A review. *Journal of Environmental Management*, *283*, 111977.https://doi.org/10.1016/j.jenvman.2021.111977

Wen, B., Li, L., Zhang, H., Ma, Y., Shan, X. Q., & Zhang, S. (2014). Field study on the uptake and translocation of perfluoroalkyl acids (PFAAs) by wheat (Triticum aestivum L.) grown in biosolids-amended soils. Environmental pollution, 184, 547-554. DOI: 10.1016/j.envpol.2013.09.040

White, S. S., Fenton, S. E., & Hines, E. P. (2011). Endocrine disrupting properties of perfluorooctanoic acid. The Journal of steroid biochemistry and molecular biology, 127(1-2), 16-26. doi: 10.1016/j.jsbmb.2011.03.011

Wickham, G. M. (2020). Emerging Contaminants, Environmental Health and Activism: The Case of PFAS Contamination in NC. North Carolina State University.

Wielsøe, M., Long, M., Ghisari, M., & Bonefeld-Jørgensen, E. C. (2015). Perfluoroalkylated substances (PFAS) affect oxidative stress biomarkers in vitro. Chemosphere, 129, 239-245.

Wu, J.-y., Shen, Z.-w., Hua, Z.-l., & Gu, L. (2023). Nitrogen addition enhanced Per-fluoroalkyl substances' microbial availability in a wheat soil ecosystem. Chemosphere, 320, 138110. https://doi.org/10.1016/j.chemosphere.2023.138110.

Xinmou. W., Liang. M. & Yang Z. (2017). Effect of acute exposure to PFOA on mouse liver cells in vivo and in vitro. Journal of Environmental Science and Pollution Research, 24: 31.

Xu, B., Yang, G., Lehmann, A., Riedel, S., & Rillig, M. C. (2023). Effects of perfluoroalkyl and polyfluoroalkyl substances (PFAS) on soil structure and function. *Soil Ecology Letters*, *5*(1), 108-117. https://doi.org/10.1007/s42832-022-0143-5.

Yao, B., Sun, R., Alinezhad, A., Kubátová, A., Simcik, M. F., Guan, X., & Xiao, F. (2022). The first quantitative investigation of compounds generated from PFAS, PFAS-containing aqueous film-forming foams and commercial fluorosurfactants in pyrolytic processes. *Journal of Hazardous materials*, *436*, 129313. https://doi.org/10.1016/j.jhazmat.2022.129313.

Yao, X., Sha, S., Wang, Y., Sun, X., Cao, J., Kang, J., & Ma, Y. (2016). Perfluorooctane sulfonate induces autophagy-dependent apoptosis through spinster 1-mediated lysosomal-mitochondrial axis and impaired mitophagy. *Toxicological sciences*, *153*(1), 198-211. https://doi.org/10.1093/toxsci/kfw118

Zhang L., Duan X., Sun W., & Sun H. (2020). Perfluorooctane sulfonate acute exposure stimulates insulin secretion via GPR40 pathway. Sci Total Environ 726:138498.

Zhang, J., Pang, H., Gray, S., Ma, S., Xie, Z., & Gao, L. (2021). PFAS removal from wastewater by in-situ formed ferric nanoparticles: Solid phase loading and removal efficiency. *Journal of Environmental Chemical Engineering, 9*(4), 105452. https://doi.org/10.1016/j.jece.2021.105452

Zhang, L., Leung, M. Y., Boriskina, S., & Tao, X. (2023). Advancing life cycle sustainability of textiles through technological innovations. *Nature Sustainability*, *6*(3), 243-253. https://doi.org/10.1038/s41893-022-01004-5.

Zhu, X., Jia, X., & Zhang, Y. (2022). The physicochemical and fire extinguishing performance of aqueous film-forming foams based on a class of short-chain fluorinated surfactants. *Journal of Surfactants and Detergents*, *25*(2), 193-204. DOI:10.1002/jsde.12550