www.envsciarch.com

ENVIRONMENTAL SCIENCE ARCHIVES
ISSN: 2583-5092
Volume V Issue 1, 2026

Received: 2026/01/28
Accepted: 2026/03/25
Published: 2026/03/28

REVIEW

OPEN ACCESS

Per and Polyfluoroalkyl Substances (PFAS) in the Environment: Uptake, Bioaccumulation and Impact on Plants, Animals and Human Health

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Abstract

PFAS, the Per and Polyfluoroalkyl substances, are synthetic compounds characterized by their chemical and thermal stability. More than 14,000 compounds in this group with diverse physicochemical properties have been documented. Due to their unique oil-and water-resistant properties, PFAS have been extensively used since 1945 in various materials science applications, including refrigerants, fire suppressants, and in the textile, paint, electronics and cookware industries. Due to large-scale production and indiscriminate misuse of these compounds in various industries over the last six decades, these persistent pollutants pose a serious threat to the ecosystems worldwide. These compounds have been detected in all environmental compartments, including air, surface water, groundwater, river water, marine water, drinking water, soil, animals, breast milk, food chains, vegetables, fruits, fish, and other seafood. The major environmental sources of PFAS are industrial, household wastewater, and effluent from armed forces and firefighting facilities. PFAS in the environment adversely impact the health of aquatic animals, livestock and humans. In aquatic organisms, PFAS exposure is associated with reproductive toxicity, oxidative stress, metabolic disruption, immunological toxicity, developmental toxicity, cellular damage, and necrosis. In terrestrial animals the bioaccumulation of these compounds leads to endocrine disruption and alteration of the intestinal microbiota. Humans are exposed to these pollutants by consuming PFAS-contaminated plant produce and animal food and by drinking PFAS-contaminated water. In humans, it alters lipid metabolism, endocrine activity, thyroid gland, and mammary gland function, negatively impacts the immune system and increases the probability of lung and kidney cancers. In the 21st century, along with microplastics and antibiotic residues, PFAS are considered the most hazardous persistent organic pollutants. This review highlights the occurrence, uptake, bioaccumulation, and adverse impacts of PFAS on crop growth, aquatic organisms, terrestrial animals, and human health. The compiled data will help develop effective mitigation and management strategies for PFAS contamination.

Keywords: Per and Polyfluoroalkyl substances; Human; Environment; Plants; Fish; Animals

Introduction

Per-and polyfluoroalkyl substances (PFAS) are toxic, synthetic, and highly stable man-made hazardous organic compounds. Teflon was the first compound accidently formed in 1938 in the laboratory of the DuPont Company. Since the 1950s, these compounds have been widely used in commercial applications, including non-stick cookware coatings, adhesives, paints, fire-fighting foams, stain-resistant carpets, aviation and military materials, cosmetics, personal care products

(PCPs), electronic items, food packaging (such as pizza boxes, and popcorn bags), and in the textile and hard metal plating industries worldwide (Han et al., 2025). PFAS compounds contain the perfluoroalkyl group (C_nF_{2n+1}) attached to a carboxylic acid, sulfonate, alcohol, amino or phosphate functional group, which is attached to a nonfluorinated hydrocarbon (Costello and Lee, 2020).

Approximately 14,000 PFAS structures with diverse physical and chemical properties have been reported (Ackerman Grunfeld et al., 2024) to date. These compounds have one of the strongest single covalent bonds in organic chemistry, imparting useful and unique properties such as thermal stability, chemical inertness, and water and oil repellence. Owing to these characteristics, these compounds have become key players in the innovative development of material chemistry for improving human life. The major applications of PFAS in modern society are listed in Table 1.

Table 1. Applications of Per and Polyfluoroalkyl substances (PFAS) in different industries /for humankind

Industry	Application of PFAS
Aerospace	Cables and wires that are associated with communication and facilities, Corrosion protection, lubricant and elastomeric seals in Turbine-engine, Jet engine/satellite instruments. Protects wire and cables from high-temperatures. Used in the propellant system as fuels and oxidizers and as aerosol propellant. PFAS are coated to protect underlying polymers from atomic oxygen effects.
Refrigerant system	Acts as heat transfer liquid in air conditioners and lubricants in compressors.
Ammunition	Makes them shockproof and rubbery to prevent unplanned explosions and enable them for long-term storage without decay.
Automotive Industry	Used in weather-resistant paint; used as sealants and bearings in automotive engines; in engine oil coolers, steel hydraulic brakes; in windshield wiper fluid; in brake pads; in cables and wires.
Biotechnology	Enhance cell cultivation by supplying oxygen and other gases to microbial cells and prevent bacterial growth.
Building and Construction	PFAS-containing composite wood and oriented strand board are used in roofs of houses and Greenhouses for protection from weathering; acts as a dirt repellent and used for light, retards cement shrinkage, to protect wire and cables, gasket and hoses from high-temperature
Chemical Industry	Used as a solvent; in the processing of molybdenum, niobium and Tantalum; helps in the processing of high- and linear low-density polyethene film, Fluoropolymer processing and polymer curing.
Cleaning	PFAS provides stain resistance and repels soil is used as a dry-cleaning liquid for cleaning Carpets and upholstery, and is also used as a cleaning fluid for adhesives.
Effluent water treatment	Filter membranes used in the treatment plants are composed of polymeric PFAS.
Electronic Industry	PFAS are used for testing electronic devices and equipment. Used for cooling of electronic and electrical equipment, in cell phones, disk drives, printers, digital cameras, zinc and lithium batteries, optical fibres, scanners, solar collectors, and coatings, magnetic recording devices, radar and satellite communication, electrical wire insulation
Electroplating	PFAS act as mist suppressants in metal plating, used in chrome plating; copper, nickel and tin plating; to deposit fluoropolymer particles on steel.
Energy Sector	Used in lithium batteries, wind mill blades, photovoltaic cells, and power plants (coal-based);solar collectors; removal of fly ash from the hot smoky discharge; and in vanadium redox batteries.
Fire-fighting foam and flame retardants	Used for fire retardation; fire training; flammants
Food Production	Used in wines and dairy products before bottling to resist degradation.
Laboratory equipment and instrumentation	Vials, globes, caps, tape used in the laboratory, seals membranes in autoclaves, ovens, oils and grease in pumps, membranes used for filtration and solvents in LC columns contain fluorinated compounds. These compounds are also used for the estimation of phosphoamino content in proteins.
Medical field	Used in defibrillators: pacemakers, cardiac resynchronization therapy (CRT; magnetic resonance imaging (MRI) & positron-emission tomography (PET); Video endoscope devices; X-ray imaging films; surgical sheets, drapes and gowns; contact lenses; eye drops; blood substitutes; stent grafts, catheters; hernia patches, joint repair and replacement lenses, eye drops; tubing, O-rings, seals and gaskets, membranes used in dialysis machines.
Nuclear Sector	In UF_6 enriched nuclear plants are used as a lubricant for valves and ultracentrifuges bearings.
Oil and Gas Sector	Used as drilling fluid, completion fluids, foaming agent, and insulating material for drilling cable and wires; lining of oil and gas pipes; helps in evaporation loss of

	oils and safe transport; used for oil and fuel filtration.
Metallic surfaces	Prevents steel corrosion, enhances the life of the alkali bath, and helps in the pickling of steel wires. Prevent cracks in the metal coating during drying; used in guitar strings, and piano keys.
Mining	Help in the extraction of metals from soil; separation of Uranium and Vanadium from ores and in solvent regeneration .
Coatings, paints and varnishes	Used to manufacture anti-stick, durable, anti-corrosive, oil and water repellents, all-weather coating paints on the exterior, interior walls and on ships.
Cosmetics & Personal Care Products	Sunscreen, shaving cream, hair conditioners, shampoo, creams, toothpaste, dental flosses, chewing gums, lipstick, nail polish, foundation, hand sanitizers, etc.
Plastic and Rubber Industry	Used as an anti-blocking agent in rubber production; retards imperfection on the moulded surface; enhances the efficiency of the polymer process. Fluoroelastomers are used as an additive in curatives, used to bond rubber to steel.
Pharmaceutical Industry	Used as reaction vessels, stirrers, in an ultrapure water system, as a moisture barrier film for packaging and in the manufacturing of microporous particles.
Photographic Industry	Used as photographic films, plates and papers; in the photographic processing solution.
Sports Material	Used in boat equipment; in Tennis rackets; golf gloves ;bicycles (Lubricant); fishing lines; climbing ropes; golf gloves.
Textile, leather and Apparel Industry	PFAS are used to make fibre stain, oil and water repellent, for dyeing and bleaching of textiles, textile treatment baths and in the finishing process of the fibre.
Tracing and Tagging	Used for tracing gas and petroleum reservoirs; pollutants in the air, leaks in pipelines, and underground storage tanks.
Wood Industry	Used for the clear coating on wood, adhesive resins are used in the wood industry; wood particle board
Other applications	Used in the glass industry, to preserve the historical manuscripts, and to manufacture non-sticking utensils.

The high thermal and chemical stability of PFAS renders them resistant to oxidation and degradation, allowing them to remain in the environment for a very long period. Since 1950, these compounds have been widely used in industrial applications, and of numerous studies. Tang et al. (2025) and Evich et al. (2022) have reported the presence of these compounds not only in aquatic and terrestrial environment (air, groundwater, surface water, marine water, drinking water, and soil), wildlife, and human bodies, but also in remote and pristine environments such as Antarctica, the Arctic, Mount Everest, and the Mariana Trench.

Several researchers (Gautam et al., 2025; Habib et al., 2024; Wee &Aris, 2023) have reported the presence of PFAS residues in human and animal blood, urine, milk, tissues, and organs, as well as in aquatic flora and fauna. Studies have also shown that terrestrial ecosystems have been significantly impacted by environmental PFAS contamination (Wee_Aris, 2023).

Soil, an integral part of the environment and ecosystem, serves as a natural medium for plant growth and food production. The protein component of soil organic matter acts as a sorbent for PFAS (Bolan et al., 2021). The widespread global detection of PFAS in soils indicates that soil functions as a reservoir for these persistent pollutants. Soils near PFAS manufacturing industries, exposed to aqueous film-forming foams (AFFFs) or amended with high amounts of biosolids, have higher concentrations of these compounds, suggesting that the untreated wastewater and biosolids used by farmers for agricultural purposes are the major sources of these compounds in soil. The accumulation of these undesirable organic pollutants in soils not only impacts soil enzyme activities and damages the cellular structure and gene expression of soil bacteria, but also has an impact on the health of humans and animals, food quality, and social development (Han et al., 2025; Jolankai et al., 2025). These pollutants accumulate in plants (via roots) and also contaminate surface, ground and marine water. The presence of these pollutants in rivers and seawater poses health risks to fish and other seafood (Abunada et al., 2020).

This study aims to provide an up-to-date review of the recent findings on the impacts of PFAS on plants and crops, as well as their implications on the health of animals and humans.

Environmental sources of PFAS

Owing to their unique characteristics (oil and water repellence, chemical resistance), PFAS are used in several industries, such as fire-fighting foams. Environmental sources of the PFAS include manufacturing and industrial sites, wastewater, wastewater treatment plants, surface runoff, precipitation, and atmospheric deposition of volatile PFAS (Ackerman Grunfeld et al., 2024; Ruyle et al., 2021). PFAS can move over long distances because of their chemical stability. Studies have shown that these chemicals cycle between ecosystems, moving from terrestrial to aquatic environments and vice versa via precipitation, leaching, partitioning and deposition processes (Gautam et al., 2025; Islam et al., 2023). Studies have shown that short-chain PFAS are highly mobile, more stable and easily accumulated in the environment (Kannan et al., 2025), where as long-chain PFAS are more easily bioaccumulated in humans, animals, soils, and sediments. Bioaccumulation of PFAS in humans and animals occurs through contaminated water (public water systems, drinking water wells), surface water of lakes, ponds, groundwater, food packaging, food items sold in the market, fish, and indoor dust from carpets and textiles (Andrusyshyna et al., 2025; Wee & Aris, 2023).

Routes of human and animal exposure to PFAS

After PFAS release from their sources, they settle in the surrounding environment (soil, water, air, surfaces, and sediments) (Dauchy, 2023). These compounds cannot be easily degraded, and both humans and animals are exposed to these directly or indirectly (Ferretti et al., 2026; De Silva et al., 2021) as follows:

(i) Dietary intake (primary route): The gastrointestinal route is the major pathway for bioaccumulation of these chemicals in humans and animals. Exposure occurs through ingestion of contaminated food and other feeds (agricultural products, fish and other seafood), water, milk, and other beverages via the mouth (Xing et al., 2023). Humans are also exposed to leaching of PFAS in the food material via food packaging material (disposable paper cups, wraps, etc.) (Zabaleta et al., 2020).

(ii) Dermal absorption (via permeable membrane) (secondary route): Dermal exposure occurs through contact with house dust, other consumer products such as paints, carpets, technical clothing, skin creams, and cosmetics (Ferretti et al. 2026). Short-chain PFAS molecules are more easily absorbed by skin (Ragnarsdottir et al., 2024).

(iii) Inhalation (secondary route): Inhalation uptake occurs via inhalation of the PFAS- containing air, dust, fumes or contaminated vapours.

(iv)Maternal transfer (primary route): In humans, PFAS can cross the placental barrier, affecting the development of foetuses. Infants also accumulate these chemicals through breastfeeding (Ricolfi et al., 2024).

(v) Other exposure routes: Contact with treated wood, stone, cleaning products, car polishing and floor-treatment products also contribute to exposure to PFAS (Sørli et al., 2020).

PFAS in agricultural soils

Globally, most of the agricultural soils are contaminated with PFAS. These compounds enter soils through compost, biosolid amendments, irrigation with sewage water/wastewater, and application of pesticides and fertilizers (Oviedo-Vargas et al., 2025; Peter & Lee, 2025 a,b; Biswas et al., 2025). Atmospheric deposition is another source of PFAS in soil (Donley et al., 2024). Adu et al. (2023), during their studies, found that bio-solid amended soils in the USA contain PFAS up to 6000 ug/kg, whereas in Europe, soil concentrations range from tens to thousands ng/g soil (Semerad et al., 2020). The concentration of PFAS in Hungarian soils varies according to land use, ranging from 0.38-0.77ug/kg (Jolankai et al., 2025).

***PFAS in the aquatic environment*:**

Major sources of PFAS in the aquatic environments are the discharge of PFAS from manufacturing/using industries, domestic wastewater, landfill leachates, groundwater contamination from sewage-amended and/or sewage-water irrigated agricultural soils. The source of effluent, structure of PFAS (number of carbon atoms and/ or functional group present) and water solubility of the PFAS are a few factors that influence the amount of the pollutant in wastewater. Studies have shown that wastewater is the primary source of PFAS contamination in surface water, river water, groundwater, drinking water, and marine water (Xu et al., 2025; Andrusyshyna et al., 2025). The review of literature denote that PFAS concentrations in wastewater ranges from ng/L to 152 ug/L; in river water it ranges from a few ng/L to 464 ug/L; in surface water up to 84 ug/L; in ground water from 0 to 12ug/L (Petre et al., 2021); in domestic wells it was up to 68 ug/L; in drinking water ranges up to 8300 ng/L and in bottled water it reaches up to 126 ng/L (Quan et al., 2025).

Impact of PFAS on the Plants and Vegetables/Crops

Since the beginning of the 21st century, in developing countries, to eradicate malnutrition, population explosion, and prosperity, the demand for vegetables, fruits and cereals (i.e. field crops), especially among vegetarians, has increased manifold. Due to water scarcity, the treated or untreated wastewater has been used for irrigation of agricultural soils worldwide. The survey of literature indicates that globally, PFAS-contaminated wastewater or partially treated wastewater irrigates more than 20 million hectares of land. Additionally, nutrient-rich bio-solids and sewage sludge from wastewater treatment plants are commonly amended in agricultural soils worldwide to improve soil fertility. The application of pesticides also increases the PFAS concentration in soils. In the USA, approximately 14% of pesticides contain PFAS as one of the ingredients (Donley et al., 2024). PFAS accumulation in soil impacts the soil health by altering soil microbial and bacterial activity and reducing soil organic matter, bulk density and soil fertility (Wu et al., 2023; Ambaye et al., 2022). PFAS are absorbed by plant roots through epidermal cells and transported via apoplastic and symplasic mechanisms (Shen et al., 2024). Root lipid and protein contents are major factors influencing accumulation of PFAS in plant roots. Soil factors such as pH, moisture, temperature and organic carbon content also impact PFAS absorption by plant roots and their translocation to the shoots. Mei et al. (2021) have reported that uptake of these pollutants by plants increases with a rise in temperature. The accumulation of PFAS is inversely correlated with soil organic matter (Hazrati et al., 2025). The accumulation of PFAS in soil retards plant growth, reduces crop yield, and lowers nutritional quality (Li et al., 2022). Bioaccumulation of PFAS in leaf tissues was maximum, and the general order of PFAS accumulation in the different parts of plants was in the order leaves > stem/shoot > root > fruit.

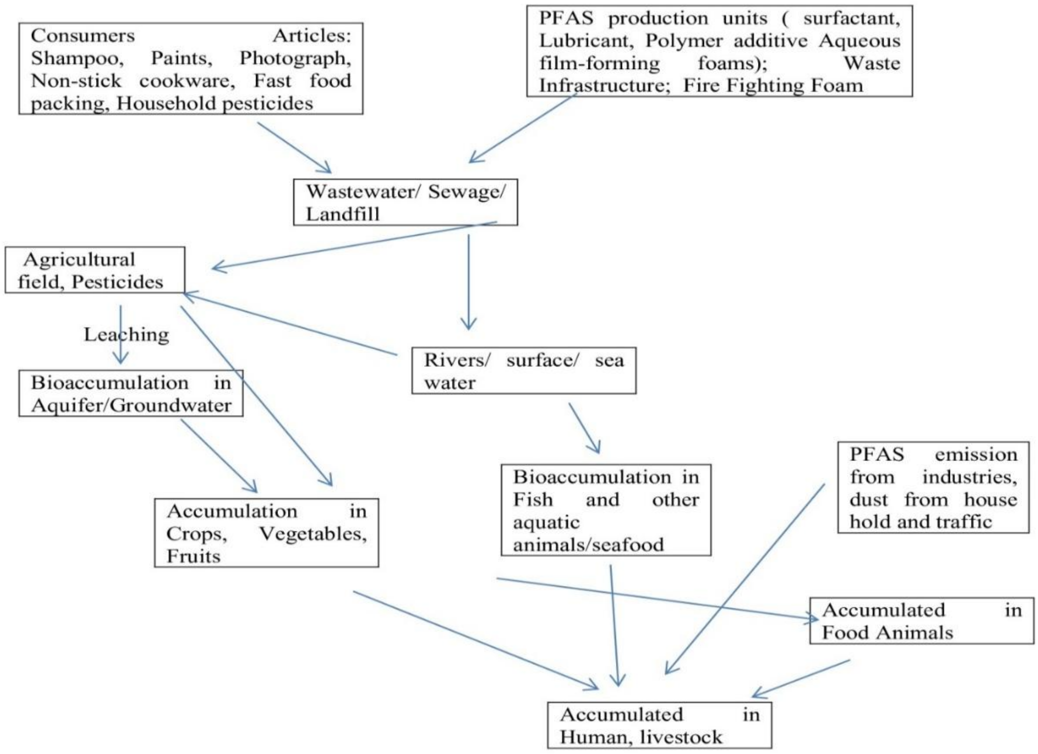

Fig. 1. Sources of the PFAS in the Environment

Carrot and radish leaves accumulated more PFAS than any other plant species. In wheat, the accumulation of PFAS was more in grains than in the stem, influenced by protein content. The studies have also revealed that short-chain PFAS are more easily translocate to the edible part. Exposure to these pollutants also decreases the chlorophyll content and root biomass (Ofoegbu et al., 2022). Prolonged exposure to PFAS reduces the K, P, Mg and sugar content in crop yield (Ebinezer et al., 2022). In the grain samples, the accumulation of short-chain PFAS was 6.2 to 59 times that of the long-chain PFAS. Bioaccumulation in plants damages cell structure and organelle functions, retards photosynthesis, carbon and nitrogen metabolism, and gene expression.

Impact of PFAS on Animals

Due to extensive industrial applications, PFAS have been reported in more than 80% of surface water, including marine water. This contamination negatively impacts the health of aquatic organisms, including fish, which are an essential part of the diet of more than 40% of the global population. Researchers have found that fish provide proteins, nutrients, omega-3 fatty acids, vitamin D, calcium, vitamin B complex, vitamin A, iron, zinc, essential fatty acids, micronutrients, and lysine. Bioaccumulation of PFAS in aquatic organisms disrupts metabolic pathways, carbohydrate metabolism, lipid homeostasis, and hormonal regulation. They also alter the gut microbiota, reducing beneficial bacteria while promoting pathogen proliferation. Reproductive toxicity, immunological toxicity, developmental toxicity, cellular damage, and necrosis have also been reported in aquatic animals due to the accumulation of these chemicals (Gasparini et al., 2024; Nayak et al., 2023). Ankley et al. (2021) found that PFAS exposure negatively impacts the growth and development of amphibians. A negative correlation between PFAS exposure/accumulation and body mass and metabolic activities in turtles was reported by Beale et al. (2022) and delayed turtle hatching by Wood et al. (2021). In fish, PFAS exposure causes endocrine disruption, with change in T_3 and T_4 levels, thyroid disturbance and neurotoxicity, with motor impairment observed by Xie et al. (2025) and Nayak et al. (2023).

PFAS in marine water, the ultimate sink of these pollutants, causes nervous disorders, reproduction failure, immune system dysfunction, liver and kidney damage, reduces organ weight, retards their potential to adjust against climate change and diseases of seafood, including fish (Alexandrino et al., 2022; Rickard et al., 2022). Neurobehavioral dysfunction upon exposure to PFAS has been reported in common carp fish by Starnes et al.

(2022). Bio magnification in fat tissues and organs results in elevated concentrations across the food chain. Liu et al. (2025) and Xie et al (2024), during their studies, reported that the physiological and biochemical functions of benthic animals are negatively impacted by PFAS; they also reported that these compounds disturb the energy activation enzymes in the animals. Roth and Petriello (2022) found that these compounds retards fat metabolism with liver and kidney damage in birds.

The accumulation of PFAS in animals causes oxidative stress, endocrine disruption, immunosuppression, respiratory effects, reproductive impairments, and adversely impacts growth; gut microbial composition, and digestive functionality (Brake et al. 2023). Cellular dysfunction due to DNA, lipid, and protein damage caused by oxidative stress has been reported in animals (ATSDR, 2021). Experimental studies have demonstrated that PFAS levels in animals are linked to cholesterol levels (Brake et al., 2023). Sun et al. (2021) reported that exposure to PFAS impairs immune function and also causes physiological impacts on nestlings. PFAS in laboratory animals and cats causes respiratory disorders that may be due to disruption in dipalmitoylphosphatidylcholine enzyme, wheezing, and nasal discharge (Brake et al., 2023; Averina et al., 2021).

In livestock (cattle, sheep, and goats), PFAS enters the body via ingestion of PFAS- contaminated grasslands or pastures and accumulated in edible tissues, organs, milk and meat (van der Fels-Klerx et al., 2024). In animals, PFAS accumulation negatively impacts the immune system, and causes liver and reproductive problems, resulting in reduced productivity (Adetunji et al., 2025).

Impact of PFAS on Humans

Exposure to PFAS for humans is via food (vegetables, fruits, fish, other seafood, and milk), water, air and contact. Endocytosis and persorption are the two pathways through which these compounds enter the human body. After entering human tissues, these compounds exert several health effects that depend on their chemical composition and the number of carbon atoms in the chain. The accumulation and exposure to these compounds in humans and animals impact the functioning of immune, gastrointestinal, respiratory, sensory, endocrine, urinary, circulatory, neurological, cardiovascular, reproductive, and mammary gland systems (Du et al., 2024; Zheng et al., 2024; Wen et al., 2023). According to Agency for Toxic Substances and Disease Registry (2021), PFAS accumulation in humans reduces serum bilirubin levels and elevates liver enzyme levels. Rosato et al. (2024) observed a positive correlation between PFAS concentration and the level of alanine transaminase (a biomarker of liver dysfunction). PFAS compounds in humans cause immune dysfunction by impacting immune organs, signalling molecules and cells (Liang et al., 2022), which increases the risk of infectious diseases and allergies (Dalsager et al., 2021a). Jones et al. (2024) and Winquist et al. (2023) found a direct correlation between PFAS concentration and leukaemia risk, a reduced vaccine efficacy upon exposure to PFAS. Zahm et al. (2024), during their research activities, concluded that PFAS accumulation weakens lymphoproliferative activity in the primary cells. A review of available epidemiological data on PFAS exposure in humans indicate that accumulation and/or exposure to these pollutants is associated with a number of cardiovascular diseases, viz., congenital heart disease, coronary artery diseases, hypertension, cardiometabolic risk, stroke, atherosclerosis, vascular dementia, endothelial damage, inflammation, impaired cardiac function, mitochondrial damage, and abnormal blood lipids. (Wen et al., 2023; Feng et al., 2022 a, b). Studies have also shown that these pollutants impact cholesterol levels in the human body (EFSA, 2020).Wang et al (2023) from their research data inferred that there is an association between serum PFAS levels and development.

Blake and Fenton (2020) found altered fetal and postnatal growth with low birth weight on exposure to PFAS during pregnancy. A number of researchers (Du et al., 2024; Tan et al., 2024) have reported that exposure to PFAS disrupts endocrine gland function. Du et al. (2024) reported a decrease in thyroid-stimulating hormone (TSH) and an enhancement in the level of free thyroxin (T_4) and triiodothyronine (T_3) in humans on exposure to PFAS. In the older population, exposure to PFAS harms the thyroid gland, according to Tan et al. (2024). As these pollutants pass from the mother to the offspring through the placental barrier, the thyroid function of the offspring is also impacted (Zhang et al., 2024; McAdam & Bell, 2023). These compounds in humans may also cause type 2 diabetes, due to endocrine disruption; the risk factors depend on the number of factors such as obesity, family history, physical activity etc. (Preston et al., 2020). PFAS exposure also causes renal dysfunction, leading to several kidney diseases and renal and genitourinary cancers (Steenland &Winquist, 2021). A literature survey denotes that PFAS in humans cause neurotoxicity, negatively affect neurodevelopment and enhance the probability of neurodegenerative diseases, as these compounds accumulate in the brain by crossing the blood-brain barrier (Ijomone et al., 2020). PFAS in the brain alters neurotransmission levels, and causes mitochondrial dysfunction and neuronal damage by enhancing oxidative stress (Xie et al., 2024; Currie et al., 2024). Several research workers have reported behavioral changes, viz., Attention-Deficit Hyperactivity Disorder (ADHD), Autism Spectrum Disorders (ASD), particularly in children exposed to PFAS (Choi et al., 2024; Kim et al., 2023; Dalsager et al., 2021b). The probability of neurodegenerative diseases such as Alzheimer's and Parkinson's with calcium dysregulation and mitochondrial dysfunction increases in older adults with the accumulation of these compounds in the brain (Song et al., 2025). Tarapore & Ouyang (2021), Yuan et al. (2020), during their studies, found that PFAS in male humans retards the development and steroid genesis in Leydig cells, resulting in abnormal development of the reproductive tract, inhibition of testosterone synthesis, which causes impaired sperm motility and retarded sperm penetration. Sabovic et al (2020) found that in young men, PFAS exposure increased the level of luteinizing and follicle-stimulating hormones which reduced sperm count and total concentration. In females, PFAS exposure delays puberty and is associated with irregular menstrual cycle. Fenton et al. (2021) showed that PFAS enhance reactive oxygen species, which results in retarding the progesterone production, causing an increase in the risk of infertility (Di Nisio et al., 2020). Zheng et al. (2024), during their research studies, found that oxidative stress, DNA damage, and hormone regulation caused by exposure to PFAS make it carcinogenic and are linked with breast (Li et al., 2022; Feng et al., 2022b), testicular (Boyd et al., 2022), kidney (Liu et al., 2023; Niu et al., 2023), thyroid and bladder cancers. Goodrich et al. (2022) found that elevated PFAS levels increase the risk of hepatocellular carcinoma. You et al. (2024) observed that the accumulation of PFAS in females was lower than in males, which may be due to childbirth and breastfeeding. Several research studies have also correlated thyroid cancer with PFAS (Zheng et al., 2024; 2023; Madrigal et al., 2024; Van Gerwen et al. 2023).

Mitigation Strategies

The research must focus on the production of environmentally friendly, non-PFAS alternatives. Industries must ensure that these pollutants are not passed in the discharged water/sludge. Aqueous film-forming foams (AFFFs) commonly used at airports, military sites, and industrial facilities must be replaced by fluorine-free foams. In wastewater treatment plants, advanced technologies such as granular activated carbon (GAC), ion exchange resins, reverse osmosis (RO), and membrane filtration must be used. Destructive technologies such as plasma technology, sonolysis, electrochemical oxidation, supercritical water oxidation, and thermal degradation /incineration may be used to remove them from the soil/sludge and water. The development of microbial degradation methods using PFAS-consuming/ degrading microbes is the need of the hour.

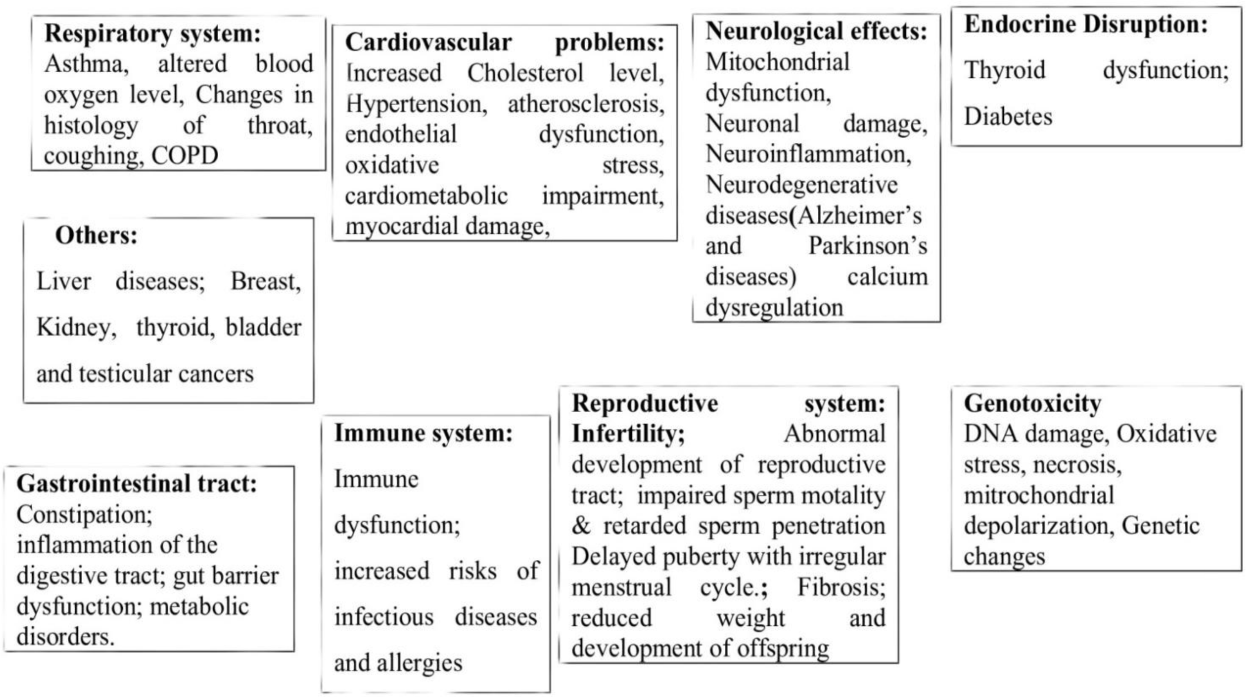

Fig. 2. Health Effects of PFAS on Humans

Conclusion

Due to the strongest covalent C-F bond, thermal and chemical stability, hydrophobic and oleophobic properties, the PFAS are considered as one of the most toxic pollutants of the 21st century. They have been detected in all segments of the environment, viz., air, soil, snow, manure, bio-solids, pesticides, groundwater, surface water, river water, drinking water, house hold wastewater, food, milk, vegetables, crops, fruits, seafood, meat, and fish and in food animals, even in remote areas like the Arctic and Antarctic. The concentration of these pollutants in wastewater, bio-solids and manure ranged from ng/g to ug/g, while in wastewater and in surface water near PFAS industries and AFFF discharge points it ranged up to mg/L. Globally more than 80% of water samples (river water, ground water, and surface water) and numerous food samples are contaminated with PFAS. Literature Surveys indicate that the maximum soil concentration reported is 7 mg/kg, and PFAS has been detected in more than 50% of all human and animal (including fish) organs worldwide. Exposure/accumulation of these compounds in animals may lead to gastrointestinal dysfunction, immune disturbances, oxidative stress, reproductive problems, and endocrine disruptions, where as in humans, it is associated with cytotoxicity, genotoxicity, apoptosis, neurodegenerative effects, and cardiovascular disorders.

The findings of this review emphasize that developing effective strategies and advanced technologies for proper PFAS management must be a top priority for environmental scientists to mitigate their persistence, bioaccumulation, and associated ecological and human health risks.

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Author Contributions
OPB conceived the concept, wrote and approved the manuscript.

Acknowledgements
Not applicable.

Funding
Not applicable.

Availability of data and materials
Not applicable.

Competing interest
The author declares no competing interests.

Ethics approval
Not applicable.

Citation: Bansal OP (2026) Per and Polyfluoroalkyl Substances (PFAS) in the Environment: Uptake, Bioaccumulation and Impact on Plants, Animals and Human Health. Environmental Science Archives 5(1): 210-222.