ECRONICON OPEN ACCESS

EC NUTRITION
Review Article

PFAS Contamination in Disposable Food Packaging: Environmental Consequences and Health Risks of Persistent Chemicals

Priyanka Nayak[1], Amit Mani Tiwari[2], Devendra Kumar Bhatt[3] and Sanjay Mishra[4]*

[1]*Regional Food Research and Analysis Centre, Sapru Marg, Lucknow, Uttar Pradesh, India*

[2]*Department of Biotechnology, Era University, Lucknow, Uttar Pradesh, India*

[3]*Institute of Food Technology, Bundelkhand University, Jhansi, India*

[4]*Department of Biotechnology, SR Institute of Management and Technology, Lucknow, Uttar Pradesh, India*

***Corresponding Author:** Sanjay Mishra, Professor, Department of Biotechnology, SR Institute of Management and Technology, Lucknow, Uttar Pradesh, India.

Received: May 04, 2026; **Published:** June 23, 2026

Abstract

Per- and poly-fluoroalkyl substances (PFAS) encompass over 7,000 synthetic compounds illustrious for their cognition to contribute resistance to fat, fire, and water in various materials, including food packaging. The chemical persistence of PFAS, attributed to the robust carbon-fluorine bonds, has earned them the label "forever chemicals". Since their introduction in the mid-nineteenth century, these compounds have expedited advancements in material sciences and different industries including textiles, electronics, and firefighting. However, their widespread application has resulted in extensive environmental contamination. They are now detectable across different environmental compartments, including air, water, soil, and biological systems like milk, fish, fruits, and vegetables. The pervasive nature of PFAS reflects an important risk to human health, with evidence linking these substances to carcinogenicity, reproductive toxicity, immune system suppression, and vaccine resistance. In response to this pressing concern, both scientific research and regulatory frameworks are evolving rapidly. This review provides in-depth reasoning of the current legislation on PFAS, advanced know-how for their detection and quantification, their toxicity profiles, and their contamination of environmental and food matrices. This review provides new insights into enhanced apprehension of PFAS impacts on future research and policy decisions.

Keywords: *Per and Polyfluoroalkyl Substances; Forever Chemicals; Human, Environment; Contamination; Milk; Vegetables; Fruits; Fish; Soil*

Introduction

Per and polyfluoroalkyl substances (PFAS) are a class of synthetic organic compounds that were first unwittingly synthesized in a DuPont laboratory in the second quarter of the nineteenth century. The breakthrough was acknowledged for its un-comparable chemical features, foremost to the commercialization of PFAS, notably Teflon, for non-stick cookware starting in the mid of the nineteenth century. The exceptional stability of PFAS, attributed to their strong carbon-fluorine bonds, supported them with noteworthy resistance to heat, water, and oil, alleviating their use across a broad range of applications. By the 1950s, PFAS had become integral to various industries,

including adhesives, fire-fighting foams, cosmetics, electronics, and textiles, where they were utilized as stain and water repellents. These applications have enabled important progression in material chemistry, contributing to societal advantages such as improved safety, convenience, and product performance. Despite their widespread use and contributions to technological innovation, the environmental persistence and bioaccumulation of PFAS have elevated concerns about their long-term impact on human health and ecosystems, persuading exaggerated examination and regulatory attention to lessen their adverse effects.

PFAS are a group of synthetic chemicals characterized by the presence of multiple carbon-fluorine (C-F) bonds, which are among the strongest covalent bonds in organic chemistry. The strength of these bonds concerns PFAS with remarkable thermal stability, chemical inertness, and both hydrophobic and oleophobic characteristics, enabling them resistant to degradation under environmental conditions [1,2]. Because of their exceptional chemical stability, PFAS prevail in the environment over prolonged periods, earning them the nickname "forever chemicals". They exhibit high mobility in the environment, leading to their detection even in remote regions such as the Arctic and Antarctic [3]. Once introduced into the food chain, PFAS are promptly bio-accumulated and biomagnified, reflecting important risks to both wildlife and humans [4]. The presence of PFAS has been documented across different environmental compartments, including air, groundwater, surface water, marine water, soil, and a wide array of consumer products. In low and middle-income countries, water deficiency often drives farmers to rely on untreated wastewater for agricultural irrigation. This exercise leads to the accumulation of various pollutants, including undesirable organic chemicals, in the soil. The concentration of these pollutants, particularly when exceeding normal levels, projects significant risks to both environmental and human health. Also, the deterioration of soil quality because of the build-up of harmful substances can reduce agricultural productivity, thereby threatening food security and quality. Furthermore, PFAS pollutants are water-soluble and can penetrate through the soil thus entering surface and groundwater systems [5]. Eventually, these contaminants can be taken up by plant roots, leading to bioaccumulation in crops and, later on, in animals that consume these plants. The presence of PFAS and other pollutants in the food chain can have serious implications for human health, contributing to several diseases and disorders. Moreover, the continual contamination of soil and water resources undermines social development by preserving cycles of poverty and environmental degradation in these regions [6]. Studies have detected PFAS residues in human biological samples like blood, urine, breast milk, and tissues, as well as in aquatic organisms, pointing to widespread environmental contamination [7]. In terrestrial ecosystems, soil serves as a critical reservoir for PFAS, where these compounds bind to organic matter, especially proteins, effectively sequestering them [8]. Notwithstanding, in regions with water scarcity, the use of untreated wastewater for irrigation exacerbates soil contamination, leading to the accumulation of PFAS beyond safe levels [9,10]. This accumulation not only degrades soil quality but also projects important risks to human health, food safety, and overall social development [11,12]. The mobility of PFAS in water systems further aids their transfer to plants and animals, hence perpetuating their presence in the food chain.

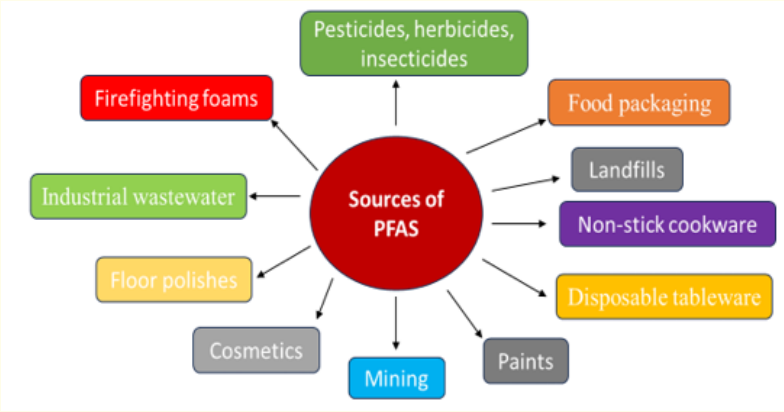

Figure 1: *Prime sources of PFAS.*

Classification of per and poly-fluoroalkyl substances

Per and polyfluoroalkyl substances (PFAS) comprehend a broad and diverse display of compounds, with estimates indicating their number ranging from 5,600 to 7,800. These substances display a wide variety of physical and chemical properties, enabling their diverse classification. PFAS can exist in several states, including gases, liquids, and solids, or as high molecular weight polymers [13]. This diversity originates from their differing chemical structures and functional groups, contributing to their multifaceted applications and behaviors in both industrial and environmental contexts. Apprehension of this range is critical for efficacious management and regulation of PFAS, given their potential environmental and health impacts.

Nonpolymers PFAS: They are fluorinated aliphatic molecules, comparatively smaller as compared to polymeric PFAS. They can be classified into following two categories.

Perfluoroalkyl substances

In this class of PFAS, all hydrogen atoms in an alkane chain are replaced by fluorine atoms. Typically, these molecules contain more than two carbon atoms and attribute a charged functional group at one end of the fluorinated chain. Their general structure can be represented as $CnF_{2n+1}R$, where "R" denotes a functional group such as carboxylate, sulfonate, or sulfonamide. Examples of PFAS include Perfluoroalkyl carboxylic acids (like PFOA), Perfluoroalkane sulfonic acids (such as PFOS), and Perfluoroalkane sulfonamides. These compounds are known for their stability and persistence in the environment, contributing to their widespread occurrence and potential health impacts [14].

Types of PFAS			Examples
Nonpolymers PFAS	Perfluoroalkyl substances (PFAS)		Perfluoroalkyl carboxylic acids Perfluoroalkane sulfonic acids Perfluoroalkane sulfonamides
	Perfluorinated alkyl substances	Perfluoroalkyl carboxylic acids	Perfluorooctanoic acid
		Perfluoroalkyl carboxylates	Perfluorooctanoate
		Perfluoroalkane sulfonic acids (PFSAs)	Perfluorooctane sulfonic acid
		Perfluoroalkane sulfonates	Perfluorooctane sulfonate
		Perfluoroalkyl phosphonic acids (PFPAs)	Perfluoropentane phosphonic acid, Perfluorooctane carboxylate (PFOA), perfluorooctane sulfonate (PFOS)
	Polyfluoroalkyl substances	Fluorotelomer Compounds	Fluorotelomer Alcohols (FTOHs), Fluorotelomer Sulfonic Acids (FTSAs), Fluorotelomer Carboxylic Acids (FTCAs)
		Per-fluoroalkane Sulfonamido Compounds	Perfluoroalkane Sulfonamido Ethanol (FASEs), Perfluoroalkane Sulfonamido Acetic Acid (FASAAs), N-Alkyl Perfluoroalkane Sulfonamides (N-alkyl FASAs)

Polymer PFAS	Fluoropolymers		Polytetrafluoroethylene (PTFE), Polyvinylidene fluoride (PVDF)
	Side Chain Fluorinated Polymers		Fluorinated urethanes, fluorinated acrylates
	Perfluoropolyether-ers (PFPEs)		Perfluoropolyether-benzophenone (PFPE-BP)
Long-chain PFAS			Perfluoroalkyl sulfonic acids (PFSAs), Perfluoroalkyl carboxylic acids (PFCAs)
Short-chain PFAS			Perfluorobutanoic acid (PFBA), Perfluorobutane sulfonic acid (PFBS)

Table 1: *Classification of PFAS based on functional side groups and length of chain.*

Perfluorinated alkyl substances

They are categorized into several key groups based on their chemical structures and functional groups.

Perfluoroalkyl acids (PFAAs) include:

1. Perfluoroalkyl carboxylic acids (PFCAs), where the functional group is a carboxyl group (COOH), such as perfluorooctanoic acid.
2. Perfluoroalkyl carboxylates, which feature a carboxylate group (COO^-), like perfluorooctanoate.
3. Perfluoroalkyl sulfonic acids (PFSAs), with a sulfonic acid group (SO_3H), exemplified by perfluorobutane sulfonic acid.
4. Perfluoroalkyl sulfonates, containing a sulfonate group (SO_3^-), such as perfluorooctane sulfonate.
5. Perfluoroalkyl phosphonic acids (PFPAs), where the functional group is a phosphonic acid (H_2PO_3), like perfluoropentane phosphonic acid. Perfluoroalkyl sulfonamides (FASAs) include compounds like perfluorooctane sulfonamide, characterized by a sulfonamide group ($-SO_2NH_2$). Perfluoroalkyl ether acids (PFEAs), such as perfluoro-2-methoxyacetic acid, have an ether linkage and a carboxyl group (OCOOH). Perfluoroalkyl aldehydes (PFALs), such as perfluorooctanal, feature an aldehyde group (-CHO). Among these, the most extensively studied are perfluoro octane carboxylate (PFOA) [$(CF_3\text{-}(CF_2)5\text{-}CF_2\text{-}COO\text{-})$] and perfluorooctane sulfonate (PFOS) [$(CF_3\text{-}(CF_2)5\text{-}CF_2\text{-}SO_3^-)$], due to their widespread environmental presence and associated health concerns.

Polyfluoroalkyl substances (PFAS)

PFAS are compounds in which not all hydrogen atoms are replaced by fluorine, resulting in molecules with one or more non-fluorinated atoms, typically hydrogen (H) or oxygen (O), attached to at least one carbon atom in the chain. These substances are generally named using the n-prefix, where "n" indicates the number of fully fluorinated carbon atoms and "x" denotes the number of non-fully fluorinated carbon atoms. Polyfluorinated PFAS can be categorized into several classes:

A.Fluorotelomer compounds: Produced through the fluorotelomerization process, this class includes:

- Fluorotelomer alcohols (FTOHs), such as [$(CF_3\text{-}(CF_2)7\text{-}CH_2\text{-}CH_2OH)$].
- Fluorotelomer sulfonic acids (FTSAs).
- Fluorotelomer carboxylic acids (FTCAs).

B. Per-fluoroalkane sulfonamido compounds: These contain a fully fluorinated carbon chain with one or more CH_2 groups attached to a sulfonamide tail, such as n-ethyl perfluorooctane sulfonamide ethanol [$(CF_3$-$(CF_2)7$-CH_2-$SO_2N(C_2H_5)$-CH_2-$CH_2OH)$]. This class includes:

- Perfluoroalkane sulfonamido ethanol (FASEs).
- Perfluoroalkane sulfonamido acetic acid (FASAAs).
- N-alkyl perfluoroalkane sulfonamides (N-alkyl FASAs).

These polyfluoroalkyl substances are noted for their unique chemical properties and environmental persistence.

Polymer PFAS: They are large molecules formed by linking numerous identical or similar small molecules, known as monomers [15]. These polymeric PFAS can be classified into several categories based on their structure and composition:

- **Fluoropolymers:** These polymers are characterized by having most hydrogen atoms in the monomers replaced by fluorine atoms, resulting in highly fluorinated chains. Common examples include Polytetrafluoroethylene (PTFE), widely used in non-stick coatings, and Polyvinylidene fluoride (PVDF), used in chemical-resistant coatings and membranes.
- **Side chain fluorinated polymers:** These compounds feature a non-fluorinated carbon backbone with polyfluoroalkyl side chains. Examples include fluorinated urethanes and fluorinated acrylates, which are employed in applications requiring enhanced resistance to stains and chemicals.
- **Perfluoropolyether (PFPEs):** In these polymers, carbon atoms are bonded with both fluorine and oxygen atoms, providing unique properties such as low surface energy and thermal stability. An example is Perfluoropolyether-benzophenone (PFPE-BP), used in specialty lubricants and coatings.

PFAS are classified based on the length of their fully fluorinated carbon chains into long-chain and short-chain categories.

1. **Long-chain PFAS:** Possess six or more fluorinated carbon atoms, such as perfluoroalkane sulfonic acids (PFSAs) and perfluoroalkyl carboxylic acids (PFCAs). These substances are known for their environmental persistence and potential for bioaccumulation.
2. **Short-chain PFAS:** These have five or fewer fluorinated carbon atoms, like perfluorobutanoic acid (PFBA) and perfluorobutane sulfonic acid (PFBS). Although generally less persistent than long-chain PFAS, short-chain variants still raise significant environmental and health concerns.

Environmental impact and health risks of PFAS

PFAS are increasingly acknowledged as a noteworthy environmental and public health interest because of their existence and widespread contamination. These synthetic chemicals frequently referred to as “forever chemicals,” do not easily degrade in the environment, leading to their accumulation in ecosystems. PFAS are highly mobile, capable of traveling great distances through air, water, and soil, and causative of widespread contamination, including in drinking water sources across Europe [16-18]. The environmental lastingness of PFAS means that even emissions today could result in environmental and health impacts for decades, if not centuries, projecting a threat to both current and future generations.

One of the major issues surrounding PFAS is their widespread use in different consumer and industrial products, including fast food packaging and disposable tableware [19]. Scientific research has progressively linked exposure to definite PFAS with a range of serious health effects, including cancer, immune system suppression, reproductive and hormonal disruptions, and even reduced effectiveness of vaccinations [20]. As scientific understanding of PFAS has grown, so too has concern over their safety. This has led to regulatory actions,

such as the European Food Safety Authority significantly lowering the recommended safe exposure levels to some PFAS by over 99% between 2008 and 2020 [21,22]. Nevertheless, despite these growing concerns and regulatory efforts, only a limited number of PFAS compounds have been limited at various levels, leaving thousands more still in use. In the food contact sector. Denmark stands out as the only country that has enacted a ban on PFAS in food packaging. Nevertheless, the industry's response has often been to substitute limited PFAS with other, less studied variants, perpetuating the cycle of potential exposure and risk [23]. This underscores the urgency for more extensive actions to lessen PFAS emissions and exposure.

PFAS in drinking water

PFAS have become a momentous public health concern because of their widespread existence in the environment, especially in drinking water. Millions of people across the United States are exposed to PFAS primarily through their drinking water [24]. The contamination of drinking water with PFAS is attributed to a variety of sources, including industrial facilities, landfills, wastewater treatment plants, and fire training sites located at airports and military bases. Despite the accepted health risks associated with PFAS, such as links to cancer, immune system effects, and other serious health conditions, there are presently no enforceable national drinking water standards in place. In 2016, the U.S. Environmental Protection Agency (EPA) issued a Lifetime Health Advisory for two of the most commonly detected PFAS-perfluorooctanoic acid (PFOA) and perfluorobutane sulfonic acid (PFOS) setting a non-enforceable guideline of 70 parts per trillion (ppt) in drinking water for these chemicals, either individually or combined (US EPA, 2016). According to national monitoring conducted by the EPA between 2013 and 2015, about 16.5 million Americans in 33 states, 03 territories, and an American Indian community are being served by drinking water contaminated with PFAS. Warningly, about six million of these individuals have water with PFAS concentrations surpassing the EPA's advisory level [25]. Nonetheless, this figure is likely an underestimation because of demarcation in the survey, such as high reporting thresholds, a focus on larger public water systems, and the restricted range of PFAS chemicals tested. Accordingly, the true scale of PFAS contamination in drinking water may be much greater than currently estimated.

S. No.	Compound	MCL (Enforceable)	MCL (Non-enforceable)
1.	PFOA	4.0	0.0
2.	PROS	4.0	0.0
3.	PFHxS	10.0	10.0
4.	PFNA	10.0	10.0
5.	HFPO-DA (Gen X)	10.0	10.0
6.	Mixtures containing two or more PFAS substances (PFNA, PFHxS, HFPO-DA, and PFBS)	1 (unitless) Hazard index	1 (unitless) Hazard index

Table 2: *Maximum contamination level of PFAS in drinking water.*

The prevalence of PFAS in cosmetics

The carbon-fluorine bonds in PFAS make them extremely resistant to heat, water, and oil. These substances are thus used in various consumer and industrial applications because of their unique properties, including stain resistance, durability, water and grease-resistance. In the cosmetics industry, PFAS are intentionally included in products such as lipsticks, eye shadows, moisturizers, rouges, nail polish and enamel, blushers, and cleansers (Figure 2). Their inclusion in these products is primarily to enhance their performance a smooth and conditioned appearance to skin and hair, improving the shine of products, or influencing their texture and consistency. Additionally, PFAS can sometimes be present in cosmetics inadvertently. This can occur through impurities in raw materials or as by-products from the breakdown of intentionally added PFAS, leading to the formation of other PFAS compounds. The persistence and

potential health risks associated with PFAS have raised concerns, leading to increased scrutiny and regulation of these chemicals in various products. One common concern is that many PFAS break down very slowly and some accumulate in people, animals, and the environment over time, posing potential health risks.

There have been restricted research remains into the presence of PFAS and its potential health risks in cosmetics.

The concentrations noticed in these products can differ importantly, ranging from parts per billion (ppb) to several hundred parts per million (ppm). One of the challenges in assessing PFAS levels in cosmetics stems from the deficiency of extensive analytical standards or "fingerprints" for many PFAS compounds. This deficiency makes it challenging to accurately detect and measure the presence of these substances, because the particular analytical methods needed to determine each PFAS variant may not be available. Therefore, the full extent of PFAS contamination in cosmetics remains uncertain, highlighting the requisite for better detection know-how and more comprehensive research in this area.

A noteworthy work published by Denmark's Environmental Protection Agency in 2018 is the most extensive risk assessment available on PFAS in cosmetics. This study particularly analyzed five kinds of PFAS impurities noticed in a range of cosmetic products, focusing on those detected most often and at comparatively high concentrations [25]. The results recommended that the levels of these PFAS impurities in the tested products are unlikely to project an important health hazard to consumers [26-28]. Nevertheless, due to the limited scope and amount of available data, no clear conclusions can be drawn about the overall potential health hazards associated with the availability of PFAS in cosmetics. Consequently, while current data suggest low hazard, the need for further research remains to amply interpret the implications of PFAS exposure through cosmetic use.

PFAS contamination in aquatic ecosystems

Industrial discharges, domestic wastewater discharges, sewage sludge, sewage water, effluent from landfills, and air emissions are direct sources of persistent pollutants, particularly PFAS, entering the aquatic environment. The concentration of these contaminants in wastewater is influenced by the source of the effluent, the physicochemical characteristics of the pollutants such as the number of carbon atoms in the chain, and the existence of particular functional groups and their water solubility. Most PFAS are extremely continual, meaning they do not promptly evaporate which contributes to their widespread environmental impact. These pollutants migrate into surface water, river water, groundwater, drinking water, marine environments, and agricultural fields through wastewater systems. Research reveals that PFAS concentrations in wastewater can range from 0.0 ng/L to 143 µg/L, whereas in river water, levels vary from a few ng/L to 496 µg/L. Surface water concentrations can reach up to 84 µg/L, and in drinking water, PFAS concentrations may rise to 8300 ng/L, highlighting the evident challenge of managing these pollutants in various water sources [28].

PFAS contamination on plant health and crop safety

The human diet consists of major components such as vegetables, fruits, cereals (field crops), as well as meat, milk, and eggs (animal-origin foods). With the advent of the 21st century, global dietary habits have shifted importantly with a consequent in a risen demand for vegetables and fruits as a result of efforts taken to decrease malnutrition, population growth, and augmented prosperity. Nonetheless, this augmented demand has led to the widespread application of treated or untreated wastewater for irrigation, with about 20 million hectares of land irrigated by raw or partly treated wastewater that is contaminated with PFAS [29]. In addition, soil contamination with PFAS is aggravated by the amendment of soils with sewage sludge or paper-fiber biosolids and atmospheric deposition. These PFAS contaminants are absorbed by plants through their roots from the soil. Globally, approximately 10% of the population consumes food grown on soils irrigated with wastewater or amended with manure. The accumulation of PFAS in plants changes depending on the number of carbon atoms in the PFAS chain and the type of plant. In general, PFAS accumulation is higher in the vegetative parts of plants compared to reproductive and storage parts, with leaves showing the greatest accumulation, followed by stems/shoots, roots, and fruits

[30]. This accumulation can cause important damage to plant cells, disrupting cell structure and organelle functions, as well as impairing photosynthesis, protein synthesis, and the metabolism of carbon and nitrogen, finally affecting gene expression and overall plant health.

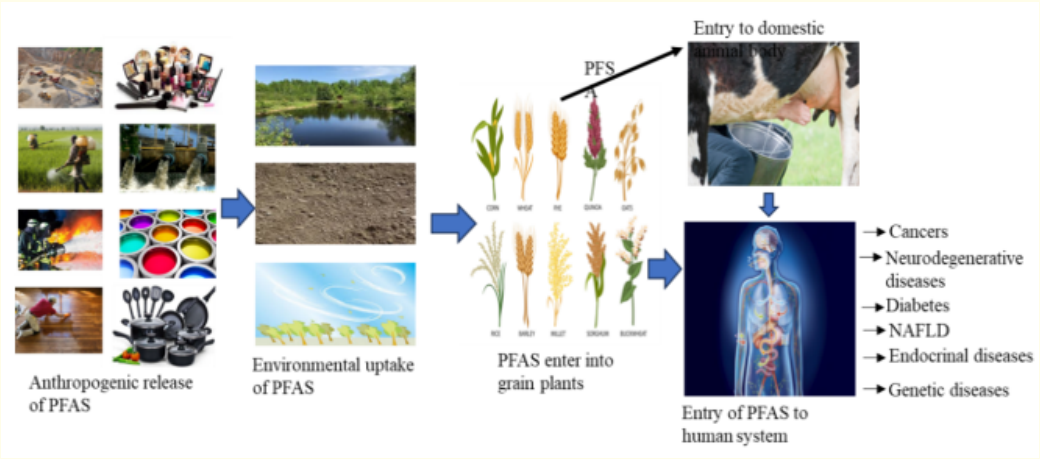

Figure 2: *The flow of PFAS particles in ecosystems and resulting human health impacts.*

PFAS contamination on fish and aquatic organisms

PFAS contamination projects a significant threat to aquatic organisms, leading to intense ecological and health impacts. When PFAS enter aquatic ecosystems, they can bioaccumulate in the tissues of fish and other organisms, leading to toxic concentrations that can interfere with various biological processes in aquatic life. It can impair fish reproduction, growth, and immune function, frequently resulting in diminished population sizes and changed community structures. In addition, PFAS contamination can affect the health of aquatic plants and invertebrates, possibly leading to broader ecosystem imbalances. The presence of PFAS in aquatic environments also poses hazards to human health, as contaminated fish may enter the food chain, leading to latent exposure and adverse effects in humans who consume these fish [30]. The complex and permanent nature of PFAS contamination hence underscores the urgent requirement for extensive environmental monitoring and remediation efforts to lessen its impact on aquatic life and ecosystems.

PFAS contamination on milk

Global per capita milk consumption is on the rise globally, driven by factors such as economic growth, population increase, and evolving dietary preferences. This trend is noticed across both developed and developing nations, where milk and dairy products are progressively becoming staples in daily diets [31,32]. India, as one of the world's largest milk producer, contributes to about 18% of the global milk supply, reflective of it's important role in approaching this growing demand. However, this increase in milk production and consumption has elevated issues about the presence of harmful contaminants, especially PFAS. Studies have detected PFAS residues in both breast milk and animal milk, posing potential health hazards. In the United States, over 80% of breast milk samples have been noticed to contain PFAS, which can bind to the β-lactoglobulin protein in milk [33]. This exposure is especially concerning for infants, as PFAS can interfere with critical aspects of their development, including immunity, hormonal balance, nervous system growth, vaccine efficacy, kidney function, and even increased risks of obesity and asthma. The presence of PFAS in milk highlights an important public health challenge, particularly given increasing milk consumption globally.

PFAS contamination in soil

Soil is undeniably the most vital natural resource on Earth, serving as the foundation for the human food system, animal fodder, and fiber production [34]. Its health is integral to human survival and overall well-being, as encapsulated by Franklin D. Roosevelt's observation: "The nation that destroys its soil destroys itself". For the past six decades, however, anthropogenic activities have significantly compromised soil health. Soils have become reservoirs for a range of pollutants, including potentially toxic metals, pesticides, antibiotics, and PFAS [34]. PFAS, in particular, infiltrates agricultural soils through various channels such as irrigation water, biosolid applications, aqueous film-forming foams (AFC) discharge, and atmospheric deposition. These contaminants either adhere to soil particles or dissolve into the soil solution, where they can be absorbed by plant roots or leached into groundwater [35]. Numerous agricultural scientists have documented global soil contamination with PFAS, underscoring the urgent need to address these pollutants to protect soil health and, consequently, human and environmental well-being.

Growing health concerns over PFAS contamination

PFAS exposure in humans can have some serious health impacts that could be lethal over time. PFAS accumulation in human body can affect their immune system, affect liver and kidney function, change puberty, increases the risk of breast, testicular, prostate, and ovarian cancers as well as with non-Hodgkin's lymphoma II [36]. PFAS can also act as an endocrine disruptor by affecting thyroid hormone levels, for example by reducing levels of the thyroid hormones, triiodothyronine (T3) and thyroxine (T4) in the human body [37]. PFOA has been revealed to competitively bind to the thyroid transport protein transthyretin (TTR) which can also lead to reduced thyroid hormone levels [38,39]. Thyroid hormones are crucial for many physiological processes like the regulation of metabolism, bone remodeling, cardiac function, and mental status. They are especially critical during fetal development because the development of the brain is dependent on the mother's levels of thyroid hormones being within the normal range [40].

PFAS are widely used in different professional and consumer products, leading to multiple pathways for their release into the environment and subsequent exposure to humans and wildlife. These compounds are continual, bio-accumulative, and resistant to environmental degradation, making them an important concern. Some PFAS have the quality to accumulate in the tissues of animals, including humans, and plants. Because of their low excretion rates, certain PFAS can build up over time in the bodies of living organisms, especially as these organisms proceed to be exposed to them. This bioaccumulation is aggravated as one moves up the food chain, leading to progressively higher concentrations of predators at the top, including humans.

The impact of PFAS on humans is elaborately connected to the route, duration, and concentration of their exposure. Research has revealed that PFAS, particularly PFOA and PFOS, have important unfavorable effects on human health. These chemicals can disrupt immune system function, alter lipid metabolism, and interfere with endocrine and thyroid gland activities [41]. They are also connected with developmental delays in the mammary glands, increased hazard of obesity, higher rates of miscarriage, and reduced sperm count. Studies entail that PFAS exposure can lead to elevated blood cholesterol levels and is connected to various health concerns including kidney diseases, testicular and kidney cancers, increased uric acid levels, and diminished vaccine responses [42,43]. A study by [44] reveals that PFAS compounds like PFOS can increase blood cholesterol and project the hazards of several cancers. PFOS decreases cellular activities, increases reactive oxygen species (ROS) levels, and affects mitochondrial function, leading to enhanced apoptosis and autophagy. Further studies, such as those by [45] have reported increased endoplasmic reticulum stress because of PFAS and a group of researchers [46] found that PFOS disrupts redox balance and abnormal autophagy, with decreased glutamine synthase activity. The prolonged PFHxS exposure was ascertained in pregnant women significantly increasing the risk of developing preeclampsia [45], while other research has revealed a positive correlation between PFOS exposure and elevated blood glucose levels [47,48]. PFAS, peculiarly long-chain compounds such as PFOA and PFOS, have been the focus of numerous epidemiological studies investigating a broad spectrum of health impacts. These studies predominantly analyze three fundamental populations: occupationally exposed workers in PFAS

production or usage facilities, communities residing near manufacturing plants with elevated PFAS levels in drinking water, and common populations exposed to background levels of these compounds. The epidemiological evidence recommends latent associations between PFAS exposure and several health outcomes across various biological systems. For example, hepatic and metabolic toxicity has been determined, characterized by liver impairment (evidenced by increased serum enzymes and decreased bilirubin) and dyslipidemia, with elevated levels of total and LDL cholesterol being most noteworthy. Reproductive and developmental toxicity has also been connected with PFAS, including reduced fertility, augmented hazard of pregnancy-induced hypertension or preeclampsia, and minor reductions in birth weight per unit increase in serum PFAS concentration. Immuno-toxicity is another issue, with evidence highlighting decreased antibody responses to vaccines [49,50]. In addition, PFAS exposure has been connected to endocrine disruption, especially a raised hazard of thyroid disease. It is crucial to note that the bulk of these studies are cross-sectional, limiting their ability to find causality definitively. Furthermore, the associations observed in various studies while being statistically significant, may not fully reflect clinically meaningful outcomes, as the magnitude of the alterations might be within normal ranges or not directly suggestive of adverse health impacts.

Conclusion and Future Perspectives

PFAS are among the most hazardous pollutants of the 21st century because of their pervasive presence across all environmental compartments. The chemical stability of PFAS, attributed to their strong C-F bonds, makes them extremely resistant to degradation. This stability permits them to endure in the environment for lengthy periods, earning them the nickname "forever chemicals". In environmental matrices like biosolids and manure, PFAS concentrations range from nanograms to micrograms per gram. In surface water near industrial sites and areas with AFFF (aqueous film-forming foam) discharge, concentrations can reach milligrams per liter. Soil near these discharge points can have PFAS levels up to 7 milligrams per kilogram. In agricultural systems, PFAS enter through manure and contaminated irrigation water, disrupting soil ecological balance. Short-chain PFAS easily move into plant components consumed by humans and animals, while long-chain PFAS remain in plant roots. These pollutants can undergo glycosylation in plants and bio-accumulate in the liver, muscle, and fillet of fish like rainbow trout. Human exposure to PFAS, through contaminated food and water, can unfavourably affect health. It impacts the immune system, lipid metabolism, endocrine and reproductive systems, and can lead to developmental issues and cancer. The magnitude of health effects changes according to concentration, exposure route, and duration. The challenges projected by different classes of PFAS require immediate action globally. First, there must be a cooperative effort to reduce the production and utilization of these harmful substances. Apart from that rresearchers should prioritize discovering alternative compounds that are less toxic and more efficient, minimizing environmental and health impacts. Besides, it is crucial to advance technology designed to efficaciously remove pollutants from wastewater, ensuring cleaner water sources. Finally, increasing awareness among the public about the detrimental effects of these pollutants is essential for encouraging a more informed and proactive society. Taken together the previous relevant studies [51-53], The concerted efforts highlighted in the present overview could thus help mitigate the negative impacts of pollutants and promote a healthier and more sustainable environment in future.

Acknowledgement

The present overview is an outcome of collaboration among researchers of four institutions of India, namely, SR Institute of Management and Technology, Lucknow, Regional Food Research and Analysis Centre, Sapru Marg, Lucknow and Era University, Lucknow and Bundelkhand University, Jhansi.

Authors' Contributions

This work was carried out in collaboration among all authors under the mentorship of Prof. Sanjay Mishra. All authors read and approved the final manuscript.

Disclaimer (Artificial Intelligence)

Authors hereby declare that NO generative AI technologies such as large language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Conflict of Interests

Authors declare no conflict of interests.

Bibliography

1. Bansal OP., *et al*. "Per and polyfluoroalkyl substances (PFAS) in the environment: A review". *Journal of Advanced Scientific Research* 13.7 (2022): 01-25.

2. Borghese MM., *et al*. "Association of perfluoroalkyl substances with gestational hypertension and preeclampsia in the MIREC study". *Environment International* 141 (2020): 105789.

3. Jose L Roscales BR., *et al*. "Levels and trends of perfluoroalkyl acids (PFAAs) in water (2013-2020) and fish from selected riverine basins in Spain". *Chemosphere* 286.3 (2022): 131940.

4. Daniele AM., *et al*. "Bioaccumulation of Per- and polyfluoroalkyl substances (PFASs) in a tropical estuarine food". *Science of the Total Environment* 754 (2021): 142146.

5. Kotlarz N., *et al*. "Measurement of novel, drinking water-associated PFAS in blood from adults and children in Wilmington, North Carolina". *Environmental Health Perspectives* 132.2 (2024): 29002.

6. Krupa PM., *et al*. "Chronic aquatic toxicity of perfluorooctane sulfonic acid (PFOS) to *Ceriodaphnia dubia*, *Chironomus dilutus, Danio rerio*, and *Hyalella Azteca*". *Ecotoxicology and Environmental Safety* 241 (2022): 113838.

7. Bolan N., *et al*. "Distribution, behavior, bioavailability, and remediation of poly- and per-fluoroalkyl substances (PFAS) in solid biowastes and biowaste-treated soil". *Environment International* 155 (2021): 106600.

8. Brevik EC., *et al*. "Communicating the importance of soils to human health: new options and opportunities". *Air, Soil and Water Research* 13 (2021): 1-23.

9. Abunada Z., *et al*. "An overview of per- and polyfluoroalkyl substances (PFAS) in the environment: source, fate, risk and regulations". *Water* 12.12 (2020): 3590.

10. Cousins IT., *et al*. "The concept of essential use for determining when uses of PFASs can be phased out". *Environmental Science: Processes and Impacts* 21.11 (2019): 1803-1815.

11. Powley CR., *et al*. "Polyfluorinated chemicals in a spatially and temporally integrated food web in the Western arctic". *Chemosphere* 70.4 (2008): 664-672.

12. Rotander A., *et al*. "Increasing levels of long-chain perfluorocarboxylic acids (PFCAs) in Arctic and North Atlantic marine mammals, 1984-2009". *Chemosphere* 86.3 (2012): 278-285.

13. Lin Y., *et al*. "Perfluoroalkyl substances in sediments from the Bering Sea to the western Arctic: Source and pathway analysis". *Environment International* 139 (2020): 105699.

14. Gockener B., *et al*. "Human biomonitoring of per- and polyfluoroalkyl substances in German blood plasma samples from 1982 to 2019". *Environment International* 145 (2020): 106123.

15. Gebbink WA and Leeuwen SPJV. "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 (2020): 105583.

16. Flaws J. IPEN ES, Plastics, EDCs and Health: A Guide for Public Interest Organizations and Policymakers on Endocrine Disrupting Chemicals and Plastics: 91 (2020).

17. European Environmental Agency. Emerging chemical risks in Europe-'PFAS' (2019).

18. Kim JM., *et al*. "Association between perfluoroalkyl substances exposure and thyroid function in adults: A meta-analysis". *PLoS One* 13.5 (2018): e0197244.

19. Beaudoina EC., *et al*. "Exposure to perfluoroalkyl substances (PFAS) and associations with thyroid parameters in First Nation children and youth from Quebec". *Environment International* 128 (2019): 13-23.

20. Hamers T., *et al*. "Transthyretin-binding activity of complex mixtures representing the composition of thyroid-hormone disrupting contaminants in house dust and human serum". *Environmental Health Perspectives* 128.1 (2020): 17015.

21. Fenton SE., *et al*. "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 (2021): 606-630.

22. Vestergren R and Cousins IT. "Tracking the pathways of human exposure to perfluorocarboxylates". *Environmental Science and Technology* 43.15 (2009): 5565-5575.

23. Vidal PC., *et al*. "Plant uptake of perfluoroalkyl substances in freshwater environments (Dongzhulong and Xiaoqing Rivers, China)". *Journal of Hazardous Materials* 421 (2022): 126768.

24. Barton KE., *et al*. "Sociodemographic and behavioral determinants of serum concentrations of per- and poly-fluoroalkyl substances in a community highly exposed to aqueous film-forming foam contaminants in drinking water". *International Journal of Hygiene and Environmental Health* 223.1 (2020): 255-266.

25. Li X., *et al*. "Assessment of per- and poly-fluoroalkyl substances in Biscayne Bay surface waters and tap waters from South Florida". *Science of the Total Environment* 806.1 (2022): 150393.

26. Ali AM., *et al*. "Legacy and emerging per- and polyfluorinated alkyl substances (PFASs) in sediment and edible fish from the Eastern Red Sea". *Environmental Pollution* 280 (2021): 116935.

27. Lee YM., *et al*. "Concentration and distribution of per- and polyfluoroalkyl substances (PFAS) in the Asan Lake area of South Korea". *Journal of Hazardous Materials* 381 (2020): 120909.

28. Macheka LR., *et al*. "Determination and assessment of human dietary intake of per and poly-fluoroalkyl substances in retail dairy milk and infant formula from South Africa". *Science of the Total Environment* 755 (2020): 142697.

29. Hill NI., *et al*. "A sensitive method for the detection of legacy and emerging per- and polyfluorinated alkyl substances (PFAS) in dairy milk". *Analytical and Bioanalytical Chemistry* 414.3 (2022): 1235-1243.

30. Galloway JE., *et al*. "Evidence of air dispersion: HFPO-DA and PFOA in Ohio and West Virginia surface water and soil near a fluoropolymer production facility". *Environmental Science and Technology* 54.12 (2020): 7175-7184.

31. Fenton SE., *et al*. "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 (2021): 606-630.

32. Conti A., *et al*. "Perfluorooctane sulfonic acid, a persistent organic pollutant, inhibits iodide accumulation by thyroid follicular cells *in vitro*". *Molecular and Cellular Endocrinology* 515 (2020): 110922.

33. Temkin AM., *et al*. "Application of the key characteristics of carcinogens to per and polyfluoroalkyl substances". *International Journal of Environmental Research and Public Health* 17.5 (2020): 1668.

34. Habib Z., *et al*. "Overview of per- and polyfluoroalkyl substances (PFAS), their applications, sources, and potential impacts on human health". *Pollutants* 4.1 (2024): 136-152.

35. Verner MA., *et al*. "Associations of perfluoroalkyl substances (PFAS) with lower birth weight: an evaluation of potential confounding by glomerular filtration rate using a physiologically based pharmacokinetic model (PBPK)". *Environmental Health Perspectives* 123.12 (2015): 1317-1324.

36. Steenl K., *et al*. "Serum perfluorooctanoic acid and birth weight: an updated meta-analysis with bias analysis". *Epidemiology* 29.6 (2018): 765-776.

37. Wouter A Gebbink., *et al*. "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 (2018): 105583.

38. Zheng G., *et al*. "Elevated levels of ultrashort- and short-chain perfluoroalkyl acids in US 2023 Homes and People". *Environmental Science and Technology* 57.42 (2023): 15782-15793.

39. Ghisi R., *et al*. "Accumulation of perfluorinated alkyl substances (PFAS) in agricultural plants: A review". *Environmental Research* 169 (2019): 326-341.

40. U.S. Food and Drug Administration. Per and Polyfluoroalkyl Substances (PFAS) in Cosmetics.

41. US. Environmental Protection Agency "Fact Sheet: PFOA and PFOS Drinking Water Health Advisories", EPA 800-F-16-003, November 2016.

42. The EPA monitored PFAS in public water systems under the Unregulated Contaminant Monitoring Rule (UCMR3) May, 2012, which monitors for emerging contaminants of concern that are not yet regulated.

43. Lin X., *et al*. "Characteristic and health risk of per- and polyfluoroalkyl substances from cosmetics via dermal exposure". *Environmental Pollution* 338 (2023): 122685.

44. Dewapriya P., *et al*. "Per- and polyfluoroalkyl substances (PFAS) in consumer products: Current knowledge and research gaps". *Journal of Hazardous Materials Letters* 4 (2023): 100086.

45. Singh K., *et al*. "Per-and polyfluoroalkyl substances (PFAS) as a health hazard: Current state of knowledge and strategies in environmental settings across Asia and future perspectives". *Chemical Engineering Journal* 475 (2023): 145064.

46. Habib Z., *et al*. "Overview of per- and polyfluoroalkyl substances (PFAS), their applications, sources, and potential impacts on human health". *Pollutants* 4.1 (2024): 136-152.

47. Qu R., *et al*. "Per- and polyfluoroalkyl substances (PFAS) affect female reproductive health: epidemiological evidence and underlying mechanisms". *Toxics* 12.9 (2024): 678.

48. Andersen ME., *et al*. "Why is elevation of serum cholesterol associated with exposure to perfluoroalkyl substances (PFAS) in humans? A workshop report on potential mechanisms". *Toxicology* 459 (2021): 152845.

49. Rhea S., *et al*. "Serum per- and polyfluoroalkyl substances (PFAS) concentrations and anti-spike SARS-CoV-2 IgG levels following COVID-19 vaccination: A cross-sectional study in three communities with elevated PFAS exposure". *International Journal of Hygiene and Environmental Health* 273 (2026): 114755.

50. Falls TA., *et al*. "Increasing PFAS concentrations in human serum correlate with elevated blood lipid levels". *Environmental Science* 5.3 (2026): 885-899.

51. Mudgal V., *et al*. "Effect of toxic metals on human health". *The Open Nutraceuticals Journal* 3 (2010): 94-99.

52. Mishra S., *et al*. "A review on epigenetic effect of heavy metal carcinogens on human health". *The Open Nutraceuticals Journal* 3 (2010): 188-193.

53. James J., *et al*. "A review on succession of bioremediation including microbial interventions for reducing heavy metal ions contamination of natural environment". *Journal of Microbes and Research* 1.2 (2022): 12.

Volume 21 Issue 4 April 2026