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INVITED REVIEW

Per- and Polyfluoroalkyl Substances (PFAS) Accumulation in Supply Chains: From Contaminated Agricultural Inputs to Animal Derived Foods

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ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) are a large group of synthetic fluorinated chemicals. They are widely used in industrial applications due to their thermal stability, hydrophobicity, and resistance to degradation. However, due to their extreme environmental persistence, bioaccumulative potential, and widespread occurrence in the environment, concerns have been raised at the global level. This review summarizes current knowledge on PFAS occurrence and transfer within the food supply chain, along with emphasis on their presence in agricultural inputs such as wastewater, sewage sludge, irrigation water, pesticides, and livestock feed. The transport of PFAS from the environment into crops, animal-derived foods, and aquatic systems is highlighted. Studies indicate that food consumption remains a major route of PFAS exposure. Perfluorooctanesulfonate (PFOS), perfluorooctanoic acid (PFOA), and perfluorooctanoic acid (PFHxS) were identified as key compounds and are associated with various adverse health outcomes, metabolic disruption, and potential of cancers. Hence as a response, international and regional regulatory frameworks including Stockholm Convention, European Food Safety Authority (EFSA) guidance, the REACH (EU regulation governing the manufacture and import of chemical substances) and the Packaging and Packaging Waste Regulation (PPWR), have increasingly restricted PFAS use. Overall, this review emphasizes the urgent need for improved monitoring and the development of safer alternatives to reduce PFAS contamination in food systems.

***Keywords**: PFAS, PFOA, PFHx, PPWR, Stockholm Convention*

INTRODUCTION

Per- and polyfluoroalkyl substances (PFAS) are a large group of synthetic fluorinated chemicals widely used in industrial and consumer products. This is due to their unique chemical stability and resistance properties. However, their high environmental persistence, limited understanding of their toxicological effects, and the exposure pathways have raised global concerns. This has caused for increasing demands for strict regulations and reduced usage (Glüge *et al.,* 2020; Itumoh *et al.,* 2024). Perfluoroalkyl substances are fluorinated aliphatic compounds and hydrogen atoms are completely replaced by fluorine. This forms a highly stable perfluoroalkyl chain linked to functional groups such as carboxylic or sulfonic acids. PFAS are classified into several subclasses depending on their chemical structure and functional groups. Those are perfluorinated carboxylic acids (PFCAs), perfluorinated sulfonic acids (PFSAs), perfluoroalkyl phosphinic acids (PFPiAs) and perfluorinated phosphonic acids (PFPAs) (Zhang *et al.,* 2022). PFAS are of mainly two classes as polymers and non-polymers. The non-polymer class include perfluoroalkyl acids (PFAA) ; the class to which the above-mentioned subclasses belong (Itumoh *et al.,* 2024). In simple terms, PFAS can be defined as a group of fluorinated chemicals that contain a minimum of one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it) (Zhou *et al.,* 2024). A characteristic of PFAS is their exceptional environmental persistence. They are highly resistant to natural degradation processes. While partially fluorinated precursors may undergo limited microbial transformation at the non-fluorinated portions of the molecule. This resulting perfluorinated fragments remain highly stable. The strength of the carbon–fluorine bond makes PFAS largely resistant to both biological and abiotic degradation under environmental conditions. Hence, for this reason, they are commonly referred to as "forever chemicals" (Brunn *et al.,* 2023).

PFAS are considered human-made substances used for surface coatings. PFAs' applications include pesticide formulation, medical applications, firefighting foams, building and construction, cosmetics, aviation, textile coating, paper and packaging, and food processing (Panieri *et al.,* 2022). Food contact materials are designed to come into direct contact with food during processing, storage, transport, and consumption. They are also involved in protecting food quality, safety, and shelf life. PFAS are widely incorporated in these due to their strong carbon–fluorine bonds. The bonds provide excellent resistance to heat and chemical degradation. Many PFAS can reduce surface tension. PFAS are also considered as excellent water, dirt, and oil repellents. PFAS have been identified in food packaging materials, microwave popcorn bags, and non-stick cookware, which can lead to indirect human exposure through chemical migration into food. Evidence suggests that frequent consumption of packaged or restaurant foods may be associated with elevated PFAS levels in humans (Carnero *et al.,* 2021). In addition, disposal of PFAS-containing food contact packaging materials can contribute to environmental contamination. Therefore, there is a potential risk to both human health and ecosystems (Death *et al.,* 2020).

Since the early 2000s, long-chain perfluoroalkyl acids have been increasingly detected worldwide. Regulatory actions have been considered because of evidence of their global transport, bioaccumulative potential, and diverse toxic effects. This caused for phase-out of several PFAS compounds. However, these restrictions have been followed by the introduction of alternative PFAS (Ng *et al.,* 2021). Manufacturers have shifted to short-chain PFAS (such as GenX). These were also increasingly detected in the environment. Those also exhibit significant environmental persistence (Death *et al.,* 2021). Hence, the review aims to identify the occurrence and transfer of PFAS across the food supply chain with emphasis on pathways from agricultural inputs to final animal-derived food products.

Further, this will assist in understanding contamination routes and potential human exposure.

Sources of PFAS in Agricultural Inputs

Sewage sludge, wastewater, PFAS-containing pesticides, and livestock feed have been detected as sources of PFAS. PFAS are widely studied in wastewater treatment systems. PFAS are frequently detected in both water streams and treatment by-products. During treatment processes, more hydrophobic PFAS tend to absorb into sewage sludge because of the hydrophobicity. Sewage sludge contamination has been reported globally at varying concentrations. After treatment, sludge is often converted into biosolids through processes such as digestion and composting. This may be reused or disposed of on land. This practice can introduce PFAS into soils and agricultural systems. Therefore, wastewater-derived bio-solids are an important pathway for environmental contamination and potential entry into the food chain (Zhou *et al.,* 2024). PFAS can also be released into the environment through industrial waste management processes. The processes in recycling facilities, incineration plants, and landfills are examples for that. Under certain conditions, these sources can emit PFAS into the atmosphere or allow them to leach into surrounding soils. Therefore, eventually contamination of groundwater systems can occur (Panieri *et al.,* 2022). PFAS contamination in irrigation and drainage water poses significant environmental and health risks. This is specially in large agricultural systems. Studies indicate that perfluoroalkyl acids, especially short-chain PFCAs and compounds like PFOA, are commonly dominant in surface, drainage, and receiving waters and increase along the flow path. These compounds can originate from local emission sources. Accumulate in downstream aquatic systems can occur which then lead to ecological impacts (such as wildlife exposure and risk to aquatic organisms). Human exposure through consumption of contaminated aquatic food contributes significantly to dietary intake levels. This highlights the influence of PFAS transport linked to irrigation on both ecosystem integrity and food chain safety (Zhang *et al.,* 2021).

PFAS in pesticide products are primarily introduced through fluorinated active ingredients and their degradates. A significant proportion of modern pesticide compounds containing organofluorines. Contamination can also occur through leaching from fluorinated packaging materials (Donley *et al.,* 2024). In integrated crop–livestock systems, major PFAS sources include industrial emissions, firefighting foams, and wastewater-derived inputs (such as sludge). Due to their high mobility, PFAS can transfer from soils into surface and groundwater. This lead to contamination of irrigation water and livestock drinking sources. Hence, there is potential for entering milk and meat products (Jha *et al.,* 2021). Microplastics (<5 mm) are widely distributed in marine, freshwater, and soil environments, and these particles can interact with and adsorb contaminants such as PFAS from contaminated water due to their hydrophobic surfaces. As a result, microplastics can act as carriers that facilitate the transport PFAS increasing their movement through food webs (Lee *et al.,* 2025).

Transfer through the food supply chain to animal-derived foods

PFAS in the environment transfer through the supply chain. This includes contamination in animal feed, livestock bioaccumulation (such as in eggs, milk and meat), in aquatic food systems, and in food processing and packaging. As per previous studies, diet and drinking water remain the primary routes of human exposure. Other than that, contributions are there from indoor air, dust and food (vegetables, eggs and meat). Among dietary sources, fish and shellfish were often identified as major contributors while some studies indicated beef was contributing 90% of total dietary intake (Death *et al.,* 2020). Ecological studies across different regions (such as Europe, Asia, North America, and polar environments) have confirmed the widespread presence of PFAS (specially PFOS; perfluorooctanesulfonate). Variety of wildlife species (such as polar bears, seals, dolphins, birds, and marine mammals) were identified for presence of PFAS in them. PFAS have also been detected in minor organisms (aquatic insect larvae). Minor organisms involves in transferring of PFAS from contaminated water bodies into terrestrial food webs. Higher PFAS concentrations were observed in wildlife compared to remote marine areas. This may be because bioaccumulation and bio-magnification through food chains. Overall, these findings highlight the extensive environmental distribution of PFAS and also the capacity to move across aquatic and terrestrial ecosystems (Peritore *et al.,* 2023).

Drew *et al.* (2021) examined the transfer of PFAS from contaminated drinking water into livestock. Beef cattle and sheep were used to estimate steady-state serum concentrations. Although PFAS were present in stock water, they were not detected in grass and occurred only at very low levels in soil. That indicated water as the primary exposure route. Mikolajczyk *et al.* (2024) investigated PFAS in meat from farm animals (pigs, cattle and poultry) and game species (wild boar and deer). The investigation revealed measurable contamination across all samples, while wild boar had the highest level of contamination. However, estimated dietary exposure was generally low and below established safety thresholds. This also suggested that consumption of wild boar meat contributed substantially higher PFAS intake compared to other meats.

Lasters *et al.* (2022) investigated PFAS exposure through diet occur via self-produced foods (eggs from free ranging birds). The investigation was carried out considering private gardens situated within a 10 km radius from a fluorochemical plant. Previous studies have indicated that PFOS and PFOA are frequently detected in such eggs. PFOS was the dominant compound and contamination tend to decrease with increasing distance from the plant. Feeding practices and bird age can also influence PFAS accumulation. Non-commercial feed sources (garden produce) often associated with higher concentrations. Overall, this indicates that self-cultivated food can be a significant but not recognized pathway of human PFAS exposure. A study of Göckener *et al.* (2020) also confirmed efficient transfer of PFAS from contaminated feed into eggs. Short-chain PFAAs, methyl and ethyl perfluorooctane sulfonamidoacetic acid (Me- and EtFOSAA), and PFOS in the plant based feed were the most abundant PFAS. PFOS, FOSAA, and its alkylated homologues of the highest concentrations were identified in eggs. Another study based on Netherlands and Greece revealed that home-produced eggs were contaminated with PFASs in contrast with most commercially produced eggs (from organic, battery and free range). This may due to hens' direct exposure to the outdoor environment and ingestion of contaminated soil and organisms (Zafeiraki *et al.,* 2016).

Health implications to humans

As PFAS are not metabolized by the human body, long-chain compounds (such as PFOA, PFOS, and PFHxS) have long biological half-lives in humans (~2–3.8 years, 3.4–5 years, and 5.3–8.5 years, respectively). As a result, these chemicals can accumulate in tissues over time and lead to higher levels (Clark *et al.,* 2024). According to Schoeters *et al.* (2025), human biomonitoring (HBM) studies found that a portion of the population has elevated serum PFAS levels. Associations between diet and serum concentrations suggest that exposure can be reduced through dietary changes. The study highlights the importance of controlling PFAS emissions into the environment and reducing their transfer into food sources such as fish, seafood, meat, and eggs. PFOS, PFOA, and PFHxS are the most extensively studied PFAS. They are efficiently absorbed after oral exposure. PFAS then accumulate mainly in the serum, liver, and kidneys. PFAS have been linked to various adverse health outcomes such as liver damage, cardiovascular disease, chronic kidney disease, low fertility and testicular cancer (Secretariat of the Stockholm Convention, 2026). In vitro studies indicate that PFAS can exert toxic effects on thyroid cells. This include cytotoxicity, genotoxicity, interference with thyroid hormone synthesis, thyroid peroxidase (TPO) function, and iodine uptake (Coperchini *et al.,* 2021). As per the study of Li *et al.* (2024), it was identified that PFAS exposure is associated with reproductive hormones as well (estradiol and testosterone). Perfluorooctanoic acid (PFOA) OA is classified as carcinogenic to humans (Group 1) and PFOS is classified as possibly carcinogenic to humans (Group 2B). This also reflects stronger overall evidence for the carcinogenicity of PFOA than PFOS (IARC, 2025). PFAS exposure has important health implications for children. As per the evidence, compounds such as PFOA increase the risk of asthma and PFOS impair lung function (Lee *et al.,* 2025).

Legislation and regulatory framework

In International platform, the Stockholm Convention on Persistent Organic Pollutants (POPs) has played a central role in restricting several PFAS. The Stockholm Convention on Persistent Organic Pollutants (POPs) is an international treaty focused on protecting human health and the environment.

The convention involves in eliminating or restricting persistent, bioaccumulative, toxic chemicals capable of long-range environmental transport. PFOS was listed in Annex B in 2009, while PFOA and its related compounds were added to Annex A in 2019 to the Stockholm Convention. Perfluorohexane sulfonic acid (PFHxS), salts and related compounds were listed in 2022 (Secretariat of Stockholm Convention, 2009, 2019 and 2022). European Food Safety Authority (EFSA) established a tolerable weekly intake (TWI) of 4.4 ng/kg body weight/week in 2020 for combined exposure to PFOA, PFOS, PFNA (perfluorononanoic acid), and PFHxS (Brunn *et al.,* 2023). Denmark, Germany, Netherlands, Norway, and Sweden have taken a major step in addressing PFAS pollution in Europe. Hence a proposal to European Chemicals Agency (ECHA) was submitted to ban PFAS under Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH). The five national authorities identified that risks that are associated with the production, sale, and use of these chemicals and are insufficiently controlled. Therefore it requires strict action at the EU and European Economic Area (EEA) level. In Europe and the United States, range of legislation were proposed to restrict or phase out PFAS in consumer products, while countries such as China, Japan, and South Korea are also have started to take steps towards stricter legislations (Schiavone, and Portesi, 2023). A high level of regulatory concern for PFAS is reflected in the EU Packaging and Packaging Waste Regulation (PPWR). The regulation introduces restrictions (EU 2025/40) on PFAS in food contact packaging materials placed on the market, by doing so aiming to reduce human exposure through packaging-related pathways. Overall, these international and regional regulatory actions demonstrate a growing global concern on the need to restrict and ultimately phase out PFAS.

CONCLUSION

PFAS are bioaccumulative and persistence chemicals. These chemicals have the ability to enter agricultural systems through different contaminated inputs such as wastewater, sewage sludge, irrigation water, pesticides, and livestock feed. This led to their transfer along the food chain into animal-derived foods. PFAS can accumulate in animal tissues, and exposure to compounds such as PFOS, PFOA, and PFHxS has been identified to associate with adverse health outcomes including liver, cardiovascular, kidney, as well as certain cancers. Although international and regional regulations (Stockholm Convention, EFSA guidelines, REACH, and EU PPWR) aim to reduce PFAS use and exposure, ongoing contamination and the emergence of alternative PFAS highlight the need for continued monitoring, stricter regulation world wide, and safer chemical substitutes in food production systems.

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