Food Research International 221 (2025) 117494

Contents lists available at ScienceDirect

Food Research International

journal homepage: www.elsevier.com/locate/foodres

Review

Levels of *per*- and polyfluoroalkyl substances (PFAS) in foodstuffs: a review of dietary exposure, health risks, and regulatory challenges

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ARTICLE INFO

Keywords:
PFAS
Food contamination
Fish and shellfish
Dietary exposure
Risk assessment
Human health
Short-chain PFAS
Regulatory thresholds

ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) are persistent environmental contaminants posing significant health risks through dietary exposure. This review compiles global data (November 2016–February 2025) on PFAS concentrations in food systems, including 48 studies on fish and shellfish, animal-origin food (livestock, poultry products, and milk), plant-based foods, and processed items. Seafood, especially shellfish and freshwater fish, emerges as a primary exposure route, frequently exceeding safety thresholds, with perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) as dominant contaminants. Animal-derived foods like eggs and milk also contribute significantly, particularly from contaminated regions. Plant-based foods typically show lower PFAS concentrations, although irrigation and soil pollution can increase their levels. Regional differences are notable, with elevated concentrations near industrial areas. Cooking methods affect PFAS concentrations, yet no single approach consistently reduces exposure. Health risks are especially pronounced for vulnerable groups (children, pregnant women, and frequent seafood consumers) whose dietary intake often surpasses the European Food Safety Authority's (EFSA) tolerable weekly intake. Regulatory challenges, emerging short-chain PFAS, and analytical variability persist. The pressing need for standardized monitoring, unified regulations, and targeted strategies to reduce dietary PFAS exposure and protect public health is highlighted here.

1. Introduction

Per- and polyfluoroalkyl substances (PFAS) are a diverse group of synthetic chemicals that have been widely used for over 60 years due to their unique properties (US EPA, 2025). These compounds resist heat, chemicals, and abrasion, making them valuable as dispersion, wetting, and surface-treatment agents across industries and products like food packaging, nonstick cookware, cleaning agents, and coatings (ECHA, 2024). Despite their widespread use, concerns about the environmental and health impacts of these substances have emerged only recently. From an environmental perspective, PFAS are extremely persistent and mobile, resulting in the long-term contamination of soil, surface water, groundwater, and even remote ecosystems, such as the Arctic. Their ability to bioaccumulate in aquatic and terrestrial food webs raises ecological risks, particularly for top predators and commercially important fish species (ECHA, 2024; US FDA, 2025). Regarding human health, epidemiological and toxicological studies have linked PFAS exposure to immunotoxicity, endocrine disruption, developmental and reproductive effects, liver and kidney toxicity, and increased risk of cancers (Souza et al., 2022; US EPA, 2025).

Food consumption has been identified as one of the primary routes of human exposure to PFAS (DeLuca et al., 2022; Eze et al., 2024; Holder et al., 2024; Roth et al., 2020). Recent studies have increasingly focused on measuring PFAS concentrations in foodstuffs and assessing dietary intake, particularly for well-known compounds like perfluorooctane sulfonic acid (PFOS), perfluorooctanoic acid (PFOA), due to their high exposure and toxicity profile (Domingo & Nadal, 2017; EFSA Panel on Contaminants in the Food Chain (CONTAM) et al., 2018, EFSA Panel on Contaminants in the Food Chain (EFSA CONTAM Panel) et al., 2020; US FDA, 2025). The growing interest in PFAS-related health and environmental risks among both the public and scientific community underscores the need for continued research and updated assessments of dietary exposure to these persistent chemicals. Marine organisms, followed by livestock products and plant-based foods, exhibit significant PFAS contamination, with PFOS and PFOA being the dominant profiles (Langberg et al., 2024). Additionally, emerging fluoroalkylether

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https://doi.org/10.1016/j.foodres.2025.117494
Received 9 March 2025; Received in revised form 10 September 2025; Accepted 10 September 2025

substitutes have raised unresolved environmental security concerns, while mitigation strategies remain constrained by global supply chain complexities and regulatory fragmentation (Feng et al., 2024). Current mitigation efforts include restricting the production and use of legacy PFAS through international agreements and national bans, promoting the development of safer alternatives, advancing remediation technologies such as adsorption, ion-exchange, and high-temperature incineration, and strengthening regulatory frameworks. However, as highlighted by Feng et al. (2024), these strategies are limited by uneven global regulatory adoption, challenges in ensuring the safety of replacement chemicals, and the technical and economic barriers associated with large-scale remediation. This fragmented progress underscores the urgent need for coordinated global policies and sustainable alternatives to effectively reduce PFAS exposure.

In 2012, a comprehensive review of the state of the science regarding PFAS concentrations in foodstuffs, human dietary exposure, and associated health risks was published (Domingo, 2012). This was followed by an updated literature review in 2017, which covered information from May 2011 to October 2016 (Domingo & Nadal, 2017). The interest in this topic has grown exponentially since then. Thus, a recent bibliometric analysis using Scopus revealed that the first citation linking perfluorinated compounds (PFCs, the former name of PFAS) and human health risks appeared in 1989, with some publications in subsequent years (Harris & Birnbaum, 1989; Kinney et al., 1989). However, the current century has shown a significant increase in PFAS research. A Scopus search on February 20, 2025, showed that the peak of citations for the term "per- and polyfluoroalkyl substances" occurred in 2024, with 2071 documents found out of a total of 4736 citations across all years. This was followed by 1550 documents in 2023 and 1180 in 2022. In the first two months of 2025, the number of documents related to PFAS has approached 500, surpassing the total of 392 documents published in 2019. This trend clearly demonstrates the growing interest in PFAS across various fields. Given the considerable increase in PFAS research, the current review updates our previous work (Domingo & Nadal, 2017), which covered literature up to October 2016, by synthesizing data published from November 2016 to February 2025.

1.1. Scope and methodology of the current review

A comprehensive literature review was conducted to synthesize existing evidence on the occurrence/concentrations of PFAS across diverse food matrices, alongside human dietary exposure, regional variations, and associated health risks. We searched PubMed (https://pubmed.ncbi.nlm.nih.gov), Scopus (https://www.scopus.com), and Web of Science (https://www.webofscience.com) covering the period November 2016 to February 2025. Search terms included "PFAS concentrations," "food," "fish," "shellfish," "seafood," "concentrations of PFAS in human foods," "per- and polyfluoroalkyl substances in foods," and "human dietary exposure to PFAS."

Eligible studies were required to report measured concentrations of PFAS in food items intended for human consumption. We considered studies addressing a wide range of food matrices, including seafood, livestock-derived products (such as meat, eggs, and milk), plant-based foods, and processed foodstuffs. To ensure methodological consistency, we excluded conference proceedings, review articles, and publications in languages other than English. Where possible, findings were interpreted in the context of dietary exposure assessments and compared to existing health-based guidance values. The full name of each PFAS compound mentioned in this review is provided in the manuscript's list of abbreviations.

2. Concentrations of PFAS in Food

2.1. Fish and Shellfish

Recent studies conducted worldwide have highlighted the significant presence of PFAS in fish and shellfish, which are major sources of PFAS exposure for the general population. Next, details on the available studies in the scientific databases are summarized according to the year of publication, starting in November 2016, when our previous review was finished (Domingo & Nadal, 2017). A summary of the characteristics and main results of the discussed studies in this section is presented in Table 1. This updated review also incorporates recent data on emerging short-chain PFAS, analyzes temporal trends in food contamination since 2016, and provides a comparative overview of regulatory thresholds worldwide. Together, these elements offer a comprehensive and timely assessment of dietary PFAS exposure, extending the scope of previous reviews and informing potential risk management strategies.

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Christensen et al. (2017) analyzed data from the U.S. National Health and Nutrition Examination Survey (NHANES, 2007–2014) to explore links between serum PFAS concentrations and self-reported fish (median: 1.2 meals/month) and shellfish (median: 0.14 meals/month) consumption. They measured 12 PFAS in serum samples and used regression models, adjusted for demographics and other exposures, to identify associations. Shellfish consumption correlated strongly with elevated serum concentrations of PFDA, PFOA, PFOS (median: 8.3 ng/mL), PFHxS (median: 1.5 ng/mL), MPAH, PFNA (median: 1.0 ng/mL), and PFuDA. Fish consumption showed weaker, mixed effects: lower MPAH but higher PFDE, PFNA, and PFuDA. That study confirmed shellfish as a key contributor to PFAS exposure in the U.S. population. In China, Guo et al. (2019) conducted a survey focused on the Bohai Sea, a significant shellfish aquaculture area. They analyzed 230 marine shellfish samples (five species: clams, mussels, scallops, whelks, and oysters) for 23 PFAS. Widespread contamination was found. Levels varied according to PFAS compound, species, and location. PFOA had the highest detection frequency (98.3 %) and the largest contribution to total PFAS concentrations (87.2 %), making it the primary concern. The highest PFOA level was found in clams (62.5 ng/g wet weight). The concentration trend across species was clams > mussels > scallops > whelks > oysters. Also, in China, Meng et al. (2019) investigated PFAS levels in water and fish from the Miyun Reservoir, a Beijing drinking water source. Water samples were collected from three depths, revealing no correlation between PFAS concentration and depth. PFAS concentrations in the water were relatively low, ranging from 5.30 to 8.50 ng/L, with PFBA and PFOA being the dominant compounds. In contrast, six fish species (*Cyprinus carpio, Carassius auratus, Erythroculter dabryi, Pseudohemiculter dispar, Hypophthalmichthys molitrix*, and *Siniperca chuatsi*) exhibited significant bioaccumulation of PFAS, particularly long-chain PFCAs and PFSAs, such as PFuDA and PFDA. PFAS concentrations in these fish species ranged from 1.70 to 14.32 ng/g wet weight (ww). Estimated daily intakes (EDIs) of PFAS through fish consumption (3.44–12.61 ng/kg bw/day) were substantially higher than through drinking water (0.20–0.34 ng/kg bw/day), highlighting the importance of fish as a PFAS exposure source. In the USA, Fair et al. (2019) measured 11 PFASs in muscle (fillets) and whole fish of six species (striped mullet, Atlantic croaker, spotted seatrout, spot, southern flounder, and red drum) collected from Charleston, South Carolina. Total PFAS levels were consistently and significantly higher (two- to three-fold) in whole fish compared to fillets. The mean of the sum of PFAS (ΣPFAS) concentrations ranged from 12.7 to 33.0 ng/g ww in whole fish and from 6.2 to 12.7 ng/g ww in fillets. Looking at individual whole fish, ΣPFAS ranged from 12.7 ng/g ww in striped mullet to a high of 85.4 ng/g ww in spotted seatrout. In fillets, individual values ranged from 6.2 ng/g ww in striped mullet to 27.9 ng/g ww in spot. PFOS was

Table 1
Summary of Studies on PFAS Concentrations in Fish and Shellfish.

Country/Region/ City	Specific Fish and Shellfish Analyzed	Main Results (Concentrations)	Highlights	Reference
Baltic Sea/ Finland	Baltic and freshwater fish	PFOS contributed 46–100 % of ΣPFAS*. EDIs exceeded TWI (4.4 ng/kg/week).	Moderate Baltic fish consumption surpasses EFSA safety thresholds.	Kumar et al. (2022)
Baltic Sea	Sprat, herring, salmon, trout, cod	Σ14PFAS: 1.74–3.54 µg/kg ww. PFOS contributed 56–73 % of ΣPFAS.	Sprat most contaminated; linear PFOS dominated in salmon and trout.	Mikołajczyk et al. (2023a)
Baltic Sea	Herring, cod, eelpout, guillemot	PFOS and FOSA declined 0–7 %/year (Baltic Proper); 6–16 %/year (other regions). PFNA, PFOA stable or increased.	Kattegat and Bothnian Bay showed faster PFAS declines; Bothnian Bay herring had high >C12 PFCA levels.	Soerensen et al. (2024)
Belgium	268 market foods (including crab)	43 % samples had PFAS (max: 2.85 µg/kg). One crab exceeded EU PFOA limit.	PFOS most detected (19 % samples); PFBA and PFOA also common.	van Leeuw et al. (2024)
China (Bohai Sea)	Clams, mussels, scallops, whelks, oysters	PFOA dominated (62.5 ng/g ww in clams). Detection frequency: 98.3 %.	Industrial activities linked to high PFOA levels; clams accumulated the most PFAS.	Guo et al. (2019)
China (Bohai/SC Sea)	Clams, mussels, oysters	ΣPFAS: 1.3–8.5 ng/g ww. PFOA, PFHxS dominant. Clams accumulated most PFAS.	Clam consumption poses potential health risks in Bohai Sea.	Wu et al. (2024)
China (Miyun Reservoir)	*Cyprinus carpio*, *Carassius auratus*, and four other species	PFAS in fish: 1.70–14.32 ng/g ww. EDIs via fish: 3.44–12.61 ng/kg bw/day.	Fish consumption contributed significantly more PFAS exposure than drinking water.	Meng et al. (2019)
China (Northern Bohai Sea)	15 marine fish species	ΣPFAS: 9.38–262.92 ng/g dw. Highest in viscera and gills; muscles lowest.	Industrial effluents key sources; HFPO-DA posed higher risk than PFOA.	Xiu et al. (2024)
China (Taihu Lake)	Crucian carp and other species	6:2Cl-PFESA detected (mean: 223 pg/g ww). HR for ΣPFAS in crucian carp: 1.04.	Potential health risk from frequent crucian carp consumption.	Chen et al. (2021)
China (Yellow-Bohai Sea)	1049 marine shellfish, crustaceans, fish	ΣPFAS highest in shellfish (order: marine shellfish > crustaceans > fish).	Industrial fluoropolymer sites linked to elevated PFAS.	Guo et al. (2023)
France	Mussels, oysters	PFOS median decreased over time; PFTrDA peaked at 1.36 ng/g ww (2016–2017).	Shift from PFOS to PFCAs in Mediterranean samples post-2015.	Catherine et al. (2019)
Greece	General fish and eggs	Weekly PFAS intake exceeded EFSA TWI due to fish consumption.	Fish consumption drives PFAS exposure above safe limits.	Costopoulou et al. (2022)
Japan	Edible shrimp from coastal areas	PFOS and PFUnDA dominant (46 % of ΣPFAS). ΣPFAS: 1.5–10 ng/g ww.	Estimated intake approaches EFSA TWI for heavy consumers.	Fujii et al. (2024)
Latvia	European perch	ΣPFAS: 0.27–3.50 ng/g. PFOS dominant (∼60 % of ΣPFAS).	Levels below regulatory limits; max intake could reach 45 % of EFSA TWI.	Zack et al. (2025)
Netherlands	Fish from national waters	PFOS exceeded EU water/fish standards. PFOA and PFOS decreased in Rhine/Scheldt post-2012.	PFAS omnipresent; limited temporal trends except in major rivers.	Jonker et al. (2024)
Norway	Atlantic cod, European plaice, lemon sole, European flounder	PFAS levels negligible or very low.	Minimal contamination risk for Norwegian consumers.	Parolini et al. (2020)
Pakistan	*S. seenghala*, C. mirigala	Σ17PFAS: Up to 45.4 ng/g. Long-chain PFAS (PFOA, PFOS) dominated. HR <1.	No immediate health risk, but long-chain PFAS prevalent.	Riaz et al. (2024)
Saudi Arabian Red Sea	Fish muscle and liver	Σ16PFAS – muscle: 3.89 to 7.63 ng/g dw; liver: 17.9 to 58.5 ng/g dw. PFOS was predominat. High levels of 6:2 FTS and PFBS.	Wastewater treatment plant effluents represented a significant source of PFAS	Ali et al. (2021)
South Africa	Farmed abalone, mussels, oysters, lobster	Σ11PFAS: 0.12–6.43 ng/g ww. EDIs: 0.05–1.58 ng/kg bw/day.	Low dietary intake despite PFAS detection in shellfish.	Abafe et al. (2021)
Spain (Barcelona)	Salmon, tuna, cod, cephalopods, crustaceans	PFAS in fish: 0.014–0.818 ng/g ww; seafood: 0.03–36.7 ng/g dw.	Cephalopod spleens and crustacean heads accumulated higher PFAS.	Marín-García, Fàbregas, Argenté, Díaz-Ferrero and Gómez-Canela (2023)
Sweden	Freshwater fish - perch, pike, and pikeperch muscles	PFOS: 0.3 to 750 ng/g. PFOA, PFNA, and PFHxS were < LOD	Fish consumption represented a significant dietary PFOS intake	Augustsson et al. (2021)
Switzerland	*Perca fluviatilis*, *Coregonus wartmanni*, and four other species	PFOS and PFHxS frequently exceeded EU limits. TWI exceeded in 50–100 % of some species.	High PFAS levels in freshwater fish; need for stricter regulations.	Soudani et al. (2024)
USA	General fish and shellfish consumption	Shellfish consumption linked to higher serum PFAS (PFOS: 8.3 ng/mL; PFHxS: 1.5 ng/mL; PFNA: 1.0 ng/mL).	Shellfish intake strongly associated with elevated PFAS levels in the US population.	Christensen et al. (2017)
USA (Charleston, SC)	Striped mullet, Atlantic croaker, spotted seatrout, etc.	ΣPFAS: 12.7–85.4 ng/g ww (whole fish); PFOS comprised 25.5–69.6 %.	PFOS levels in 83 % of whole fish exceeded wildlife safety thresholds.	Fair et al. (2019)
USA (commercial seafood)	70 marine/freshwater species	ΣPFAS: Mostly <1 ng/g; Great Lakes fish up to 22 ng/g. PFOS predominant.	Low PFAS exposure in most market seafood, except Great Lakes fish.	Ruffle et al. (2020)
USA (FDA TDS)	179 food samples	PFOS detected in two fish samples. Method detection limit: ∼0.4–0.5 ng/g.	Validated QuEChERS method for PFAS analysis in diverse foods.	Genualdi et al. (2021)
USA (FDA TDS)	Fish sticks, canned tuna, protein powder	PFAS detected <150 ppt.	PFOS and PFNA found in frozen fish sticks; PFOS in canned tuna.	Genualdi et al. (2022)
USA	Clams, crab, tuna, shrimp, etc.	ΣPFAS: Up to 23 µg/kg in canned clams. PFOA dominant in clams.	Highest PFAS levels in clams and crabs; no PFAS in packaging.	Young et al. (2022)
USA	Freshwater fish (500+ samples)	Median ΣPFAS: 9500 ng/kg (rivers); 11,800 ng/kg (Great Lakes). PFOS: 74 % of ΣPFAS.	Freshwater fish PFAS levels 278× higher than commercial fish.	Barbo et al. (2023)
USA (East Canyon Creek, UT)	Brown trout, mottled sculpin	Σ20PFAS: Up to 63.9 ng/g (sculpin), 52.1 ng/g (trout). PFOS predominant.	74 % of sculpin and 45 % of trout exceeded EFSA thresholds; no significant biomagnification observed.	Sapozhnikova et al. (2025)
Vietnam (Hanoi)	Common carp and three other freshwater species	PFAS in blood: 5.2–29 ng/mL; liver: 2.7–6.6 ng/g ww; muscle lower. PFOS dominant.	Over 90 % of PFAS in blood and muscle; dietary intake below safety thresholds.	Hoa et al. (2022)

Symbols: ΣPFAS: mean on the sum of PFAS; EDI: Estimated Daily Intake; TWI: Tolerable Weekly Intake; ww: wet weight; dw: dry weight; bw: body-weight; HQ: Hazardous Quotient.

the predominant compound across all species, comprising 25.5–69.6 % of the total PFAS. PFAS levels in fillets varied significantly by location, with higher ΣPFAS found in fish from the Ashley River. PFOS concentrations in southern flounder and spotted seatrout fillets were within the advisory range for limiting consumption to four meals per month. However, PFOS levels exceeded screening values designed to protect mammals in 83 % of the whole fish examined, indicating a potential risk to wildlife predators. In France, Catherine et al. (2019) measured PFAS levels in filter-feeding shellfish (primarily mussels and oysters) collected from 2013 to 2017 along the English Channel, Atlantic, and Mediterranean coasts of the country. The study focused on five PFAS: PFOS, PFTrDA, PFTeDA, PFDoA, and PFuDA, all of which were detected in more than 80 % of the samples, confirming widespread contamination of the French coastal environment. The distribution of PFAS concentrations varied by sampling location and year. PFOS was the predominant compound found in most samples collected from the English Channel and Atlantic coasts until 2014. However, a significant shift was observed from 2015 to 2017, with PFCAs becoming more prevalent in Mediterranean samples across all study years. Among the PFCAs, PFTrDA exhibited the highest maximum concentration (1.36 ng/g ww) and the highest median concentration (0.077 ng/g ww) in the 2016–2017 period. Other PFAS median concentrations were within the range of 0.014 ng/g ww (for PFNA) to 0.055 ng/g ww (for PFTeDA). PFOS median concentrations showed a significant decrease over the study years, reflecting the phase-out of PFOS production. On the other hand, Ruffle et al. (2020) examined PFAS levels in the U.S. commercial seafood supply. Seventy samples of finfish and shellfish, representing a diverse range of marine and freshwater species and various origins (including imports), were purchased at U.S. grocery stores and fish markets and analyzed for 26 PFAS. Up to ten PFAS were detected in 21 samples, with PFOS being the predominant compound. Nevertheless, a substantial portion of the samples (49 out of 70) had no detectable PFAS (with detection limits of approximately 0.4–0.5 ng/g). Total PFAS concentrations in most samples were either single-digit or sub-ng/g levels. A significant exception was commercial finfish sourced from the Great Lakes area, where higher levels (up to 22 ng/g) were observed in whitefish, walleye, and yellow perch fillets. The overall findings suggested low PFAS exposure for consumers of typical market basket fish and shellfish. In Norway, Parolini et al. (2020) measured levels of a broad range of legacy and emerging contaminants, including PFAS, in fillet samples from four demersal fish species caught in two fishing sites: Atlantic cod (*Gadus morhua*), European plaice (*Pleuronectes platessa*), lemon sole (*Microstomus kitt*), and European flounder (*Platichthys flesus*). In contrast to other studies, the researchers found negligible contamination by all investigated chemicals, including PFAS, for which very low levels were detected in only a limited number of individuals for each species. Although the specific concentrations were not reported in detail, the overall conclusion was that the risk to Norwegian consumers was minimal. In South Africa, Abafe et al. (2021) measured 15 PFAS in four species of farmed marine shellfish (abalone, mussel, oyster, and lobster). The most prevalent compounds were PFPeA, PFOS, PFHxA, and PFTeDA, with detection frequencies of 94 %, 88 %, 76 %, and 71 %, respectively. The Σ11PFAS concentrations varied across species: 0.12 to 0.49 ng/g ww in abalone, 4.83 to 6.43 ng/g ww in mussels, 0.64 to 0.66 ng/g ww in oysters, and 0.22 ng/g ww in lobster. The estimated daily intakes (EDI) for Σ10PFAS through the consumption of marine shellfish were relatively low, ranging from 0.05 to 1.58 ng/kg bw/day. In China, Chen et al. (2021) assessed the tissue distribution of legacy and emerging PFAS in several edible fish species collected from Meiliang Bay of Taihu Lake. The related human health risks and characterized PFAS exposure in Beijing residents were also assessed using dietary samples (animal-origin and vegetable). Linear PFAS were commonly found in fish, and the PFAS alternative 6:2Cl-PFESA was mainly detected in freshwater and marine fish, with a mean level of 0.000223 ng/g ww and 0.000158 ng/g ww, respectively. Branched PFOA (br-PFOA) and branched PFOS (br-PFOS) were only detected in pork liver and fish samples. The calculated EDI∑PFOA and EDI∑PFOS values were far below the tolerable weekly intake (TWI) (EFSA, 2018). PFOS, PFOSA, and 6:2 fluorotelomer phosphate diester (6:2 diPAP) were the most abundant legacy perfluoroalkyl acid (PFAA), PFOS-related precursor (PreFOS), and emerging PFAS, respectively. Bioaccumulation factors (BAFs) were calculated, and the hazard ratios (HR) of PFOS ranged from 0.0100 to 0.655, while PFOA HR was <0.00200 in all fish muscles, both below 1.0. Notwithstanding, the HR of the ΣPFASs in crucian muscle was 1.04, indicating potential risks from frequent consumption of crucian carp collected from Meiliang Bay. In turn, Ali et al. (2021) investigated the presence of 16 PFAS in edible fish from the Saudi Arabian Red Sea. The study revealed average concentrations ranging from 3.89 to 7.63 ng/g dry weight (dw) in fish muscle and 17.9 to 58.5 ng/g dw in fish liver. PFOS was the predominant PFAS detected. Notably, 6:2 FTS was found at a maximum concentration of 7.1 ng/g dw in doublespotted queenfish liver and PFBS at 2.65 ng/g dw in strong spine silver-biddy liver. The study's calculations indicated that dietary intake of PFOS, PFOA, PFNA, and PFHxS from double-spotted queenfish muscle surpassed established safety thresholds, posing a potential health concern for consumers. In Sweden, Augustsson et al. (2021) estimated PFOS intake from the consumption of freshwater fish. PFOS levels were analyzed in perch, pike, and pikeperch muscles from 78 different inland waters. The averagePFOS concentrations varied significantly, ranging from 0.3 to 750 ng/g. According to the study's estimates, "normal consumers" (eating freshwater fish three times a year) would reach their yearly tolerable intake when PFOS concentrations in fish reach 59 ng/g, while "high consumers" (consuming fish once a week) would reach it at 3.4 ng/g. PFOA, PFNA, and PFHxS were below the detection limit in the analyzed samples.

As part of the Food and Drug Administration's (FDA) Total Diet Study (TDS) program, Genualdi et al. (2021) developed and validated a method for PFAS analysis in a wide variety of foods. The extraction of 16 PFAS was performed using the QuEChERS (quick, easy, cheap, effective, rugged, and safe) method, followed by analysis using liquid chromatography/mass spectrometry. The validated method was then used to analyze 179 total diet study samples, with positive detections for PFOS found in two fish and one meat sample. The original study did not report specific concentration values. Moreover, Genualdi et al. (2022), continuing the FDA's Total Diet Study, further optimized a PFAS analysis method, addressing challenges related to method blanks and confirmation of short-chain PFAS using high-resolution mass spectrometry. In this phase of the study, positive detections of PFOS and PFNA were found in frozen fish sticks/patties, PFOS and PFDA in canned tuna, and PFOS in protein powder. Importantly, all detected concentrations were below 0.150 ng/g.

Kumar et al. (2022) analyzed PFAS levels of several fish species caught in selected Baltic Sea basins and freshwater bodies of Finland. PFOS was detected in all Baltic Sea fish samples and in over 80 % of fish samples from freshwaters. PFOS contributed significantly to the total PFAS concentration, ranging from 46 % to 100 % in Baltic Sea fish samples and from 19 % to 28 % in fish samples from freshwaters. The concentration ratios of PFOS to other PFAS differed geographically between fish from the Baltic Sea and Finnish lakes, suggesting variations in PFAS distribution. Moderate consumption of most Baltic fishes (200 g/week) was found to result in an exceedance of the TWI (4.4 ng/kg body weight/week) for Σ4PFAS (PFOA, PFOS, PFNA, and PFHxS). In Greece, Costopoulou et al. (2022) estimated human intake of the same four specific PFAS from fish, eggs, and drinking water consumption. Data from the EFSA food consumption database for fish and eggs were utilized for the assessment. The mean weekly intake estimated was found to be above the TWI (EFSA, 2018) due to fish consumption. Specific intake values were not provided within the text excerpt, but the exceedance of the TWI was a key finding. In the USA, Young et al. (2022) analyzed 81 highly consumed seafood products in the country (including clams, crab, tuna, shrimp, tilapia, cod, salmon, and pollock) for 20 PFAS. Most of the seafood packaging was also analyzed for PFAS. A wide range of PFAS concentrations was observed among the seafood samples, ranging from below the method limit of detection (LOD) to the highest concentration of 23 ng/g for the ΣPFAS in one of the canned clam samples. The highest concentrations were generally found in clams and crabs, followed by cod, tuna, pollock, tilapia, salmon, and shrimp. PFOA dominated the PFAS profile of the clam samples. Long-chain PFCAs, specifically PFuDA and PFDoA, were the most frequently detected PFAS across all seafood samples. None of the packaging samples were identified as having PFAS. In Vietnam, Hoa et al. (2022) analyzed 17 PFAS in blood, muscle, and liver samples of four freshwater fish species from West Lake and Yen So Lake, Hanoi. PFAS concentrations were highest in blood (5.2–29 ng/mL) and liver (2.7–6.6 ng/g ww), while muscle had lower levels. Over 90 % of total PFAS burdens were found in blood and muscle, with PFOS and long-chain PFAS (C10–C14) being predominant. While species showed similar PFAS levels, common carp exhibited a distinct profile with higher PFOS and long-chain PFAS proportions. Estimated dietary intake remained below both US.EPA and EFSA safety thresholds indicate low health risks from fish consumption. In China, Guo et al. (2023) measured 23 PFAS in 1049 aquatic products collected from the coasts of the Yellow-Bohai Sea. PFOA, PFOS, PFNA, PFOSA, and PFuDA were found to be more predominant and frequently detected than other PFAS. The mean levels of ΣPFAS in different species followed this order: marine shellfish > marine crustaceans > fish > cephalopods > sea cucumber. Profiles of PFAS differed between species, suggesting that species-specific accumulation plays a role. High ΣPFAS levels in some specific sites (such as Binzhou, Dongying, Cangzhou, and Weifang) were attributed to industrial activities involving fluoropolymer manufacture. Specific mean concentration values for each species were not provided within the text excerpt. In Barcelona, Spain, Marín-García et al. (2023) optimized a previous analytical method to determine 12 PFAS in fish muscle from a variety of species (salmon, tuna, cod, hake, sardine, anchovy, and sole), as well as in seven different seafood species (cuttlefish, octopus, squid, shrimp, Norway lobster, prawn, and mussel). For fish, PFAS concentrations ranged from 0.014 to 0.818 ng/g ww. Sardines, anchovies, and soles presented the highest PFAS levels, with cod samples also showing some PFAS traces. Regarding seafood, PFAS levels ranged from 0.03 to 36.7 ng/g for the studied species. A higher concentration of PFAS was found in the cephalopods' spleens and the crustaceans' heads. PFOS and PFBS were the predominant compounds in each seafood species, respectively. In contrast, in mussels (the least polluted species), contamination by longer-chained PFAS was also observed. The total intake of PFAS due to fish and shellfish consumption for the Spanish adult population was estimated at 17.82 ng/day. Nevertheless, none of the analyzed samples exceeded the EFSA risk value for the supervised PFAS in any age/gender group reviewed (EFSA, 2018). On the other hand, Mikołajczyk et al. (2023a) investigated the concentrations of PFAS in five Baltic fish species: sprat, herring, salmon, trout, and cod. Each species' median lower bound (LB) concentration of Σ14PFAS was determined as follows: sprat (3.54 ng/g ww), cod (2.15 ng/g ww), salmon (2.10 ng/g ww), trout (2.03 ng/g ww), and herring (1.74 ng/g ww). Regarding the species' median LB of Σ4PFASs (PFOS, PFOA, PFNA, and PFHxS), sprat was the most contaminated (2.90 ng/g ww), being herring the least contaminated (1.17 ng/g ww). Among all PFAS, PFOS was found at the highest concentrations, ranging from 0.04 to 9.16 ng/g ww, and its percentage share in the total concentration of Σ14PFAS was between 56 % and 73 %. The average proportion of linear PFOS (L-PFOS) in the total PFOS (branched and linear) was highest in salmon (89 %) and trout (87 %), while in the other three species it ranged from 75 % to 80 %. Dietary intake via fish consumption was estimated at 3.20–25.13 ng/kg bw for children and 1.68–8.30 ng/kg bw for adults. Barbo et al. (2023) calculated the potential contribution of PFOS from locally caught freshwater fish consumption to serum levels in the US. Data for over 500 composite samples of fish fillets were collected across the US from 2013 to 2015 and analyzed by the USEPA monitoring programs. The median level of total targeted PFAS in fish fillets from rivers and streams across the US was 9500 ng/kg, with a median level of 11,800 ng/kg in the Great Lakes. PFOS was the largest contributor to total PFAS levels, averaging 74 % of the total. The median levels of total detected PFAS in freshwater fish across the US were 278 times higher than in commercially relevant fish tested by the US.FDA in 2019–2022. Exposure assessment suggested that a single serving of freshwater fish per year with the median level of PFAS (as detected by the US.EPA monitoring programs) translated into a significant increase of PFOS levels in blood serum. Also, in the USA, Bedi et al. (2023) conducted a pilot study to screen for the presence of 33 PFAS compounds in 46 seafood samples purchased from stores across the country. The study detected PFAS in 74 % of the seafood samples, with PFHxS being the most prevalent (59 %). Concentrations varied widely, ranging from near detection limits (0.12 ng/g) to as high as 20 ng/g, with the highest values observed in smelt sourced from Estonia. The highest median levels were reported for PFOA (0.84 ng/g), while clams from China showed elevated concentrations (2.4 ng/g), surpassing EU maximum limits. Detected concentrations of PFHxS, PFOA, and PFNA also exceeded maximum limits in some samples, highlighting notable variability across species and origins.

In Japan, Fujii et al. (2024) analyzed perfluoroalkyl sulfonic acids (PFSAs, with carbon numbers from 6 to 8 and 10) and perfluoroalkyl carboxylic acids (PFCAs, with carbon numbers from 6 to 15) in 30 retail packs of edible shrimps. These included seven species from eight coastal areas of Japan and neighboring countries. The most prevalent compounds were PFOS and PFUnDA, accounting for 46 % of the total PFAS. The concentrations ranged from 6.5 to 44 ng/g dw, which is equivalent to 1.5 to 10 ng/g ww, and varied according to species and location. Regional differences were also observed, with higher concentrations of long-chain PFCAs in Japanese coastal waters than in the South China Sea. The estimated daily intake of the ΣPFAS from shrimp from Japanese coastal water was 0.43 ng/kg bw/day on average, which could reach the TWI (4.4 ng/kg bw/week) for the Σ4PFAS set by the EFSA for heavy consumers (EFSA, 2020). Recently, Jonker (2024) reported data on PFAS concentrations in Dutch inland and coastal national waters and fish sampled from 2008 to 2022 (water) and 2015 to 2022 (fish). PFAS were found to be omnipresent in Dutch water and fish, with relatively small spatial differences in absolute and relative concentrations (fingerprints) and few obvious temporal trends. Only PFOA and PFOS aqueous concentrations in the rivers Rhine and Scheldt substantially decreased since 2012. PFOS concentrations still exceeded the European water quality standards at all sampling locations and fish standards at many locations. Specific concentrations were not provided within the text, but the exceedance of standards was a key finding. Also recently, Riaz et al. (2024) carried out in Pakistan a study designed to assess PFAS contamination in muscle tissues of edible fish species from major tributaries of the Indus System. The highest levels of Σ17PFAS were observed in *S. seenghala*, *C. mirigala* from Head Blloki (HB), and *C. mirigala* from Head Qadirabad (HQ), with mean values of 45.4 ng/g, 43.7 ng/g, and 40.8 ng/g, respectively. Overall, the compositional profile of fish samples was predominated by long-chain PFAS such as PFOA, PFOS, PFHpS, and PFDS. None of the fish samples showed sufficiently high levels of PFOS to cause human health risk (Hazard Index, HI < 1). Van Leeuw et al. (2024) reported the results of a study aimed at providing a sensitive analytical method for the quantification of 25 PFAS in foods, including those for the young population and beverages, and gathering occurrence data for dietary exposure evaluation for the Belgian population. For the determination of PFAS in foodstuffs, an extraction based on the QuEChERS method and combined with a two-step purification using solid-phase extraction was optimized. The analysis of 268 food products from the Belgian market demonstrated that 43

% of samples contained at least one PFAS, with a maximum of 11 PFAS measured in a stew of wild pork. PFOS was the most detected compound, found in 19 % of samples, followed by PFBA (18 %) and PFOA (15 %), while PFTeDA, PFPeS, PFHpS, PFDS, PFUnDS, PFDoDS, PFTrDS, Minor F53B, and HFPO-DA were not detected. The concentrations of the different PFAS in commercial food varied from below the limit of quantification (<LOQ) to 2.85 ng/g, with only one crab sample exceeding the maximum level for PFOA set by the Commission Regulation (EU) 2023/915 ((EU, European Union, 2025)). In China, Wu et al. (2024) collected 76 samples of different shellfish species from the Bohai Sea and South China Sea coastal cities. Results showed that the signal response of perfluorocarboxylic acid increased with the length of fluorocarbon chains. Ten PFAS were detected in shellfish samples at concentrations ranging from 1.3 to 8.5 ng/g ww. PFOA and PFHxS were the dominant components, and PFOA, PFTrDA, and PFNA were detected at high rates of 58–93 %. The highest levels of ΣPFAS were accumulated in clams, while the lowest levels were found in mussels. The dietary risk assessment indicated that PFAS potentially threatens human health via consuming clam products in the Bohai Sea region. In the same area, Xiu et al. (2024) investigated PFAS contamination in 15 marine fish species from China's northern Bohai Sea, analyzing sources and health implications. PFAS levels ranged from 9.38 to 262.92 ng/g dw, with the highest concentrations in viscera and gills, while muscles had the lowest. Industrial effluents and sewage discharges were identified as key contamination sources. PFAS levels were not significantly linked to trophic position but increased with fish size and lipid content. A daily intake of 5 g (wet weight) from specific fish species was deemed safe for fatty acid supplementation. Soudani et al. (2024) assessed PFAS contamination in six freshwater fish species from Swiss lakes using 218 fillet samples. *Perca fluviatilis* exhibited the highest PFOS and PFHxS levels, frequently surpassing EU safety limits. TWI calculations showed exceedance in 95 % of *Coregonus wartmanni*, 100 % of *Squalius cephalus*, and over 50 % of some *Oncorhynchus mykiss*, *Salmo trutta*, and *Perca fluviatilis* specimens. Correlation analysis in *Salmo trutta* indicated positive associations between fish size and PFBS, PFDA, and PFHxS, while PFPeA showed a negative trend. The study highlighted the need for ongoing monitoring and stricter regulations to minimize PFAS exposure risks. Soerensen et al. (2024) examined the temporal and spatial trends of PFAS in herring, cod, eelpout, and guillemot across the Baltic Sea over four decades. PFAS concentrations generally declined in response to regulations, although variations were observed across basins. Kattegat and Bothnian Bay showed faster decreases than the Baltic Proper, where PFOS and FOSA declined by 0–7 % per year, compared to 6–16 % in other regions. PFNA and PFOA remained stable or increased. Bothnian Bay herring had the highest >C12 PFCA levels, while Kattegat exhibited low PFAS but a high FOSA fraction. That extensive study provided key insights into PFAS cycling in the Baltic ecosystem. In the USA, Crawford et al. (2024) analyzed 81 seafood samples (clams, crab, tuna, shrimp, tilapia, cod, salmon, and pollock) for 20 PFAS using an updated analytical method. The study found a wide range of PFAS concentrations, from below detection limits to a maximum of 23,000 ng/g for total PFAS in a canned clam sample. Clams and crabs had the highest concentrations, followed by cod, tuna, pollock, tilapia, salmon, and shrimp. Long-chain PFCAs, particularly PFuDA and PFDoA, were most frequently detected across all samples. The study noted that benthic organisms tended to have higher PFAS concentrations compared to lean fish, fatty fish, and aquaculture species. On the other hand, in an analysis of the Italian food consumption database, Brambilla (2024) found that wild seafood species like squid, cuttlefish, crustaceans, and clams contributed significantly to PFAS intake, exceeding the provisional safety threshold of 4.4 ng/kg bw/week. In Latvia, a recent study by Zacs et al. (2025) assessed PFAS contamination in European perch from freshwater bodies. Analysis of 29 tissue homogenates showed total PFAS concentrations ranging from 0.27 to 3.50 ng/g, with PFOS as the dominant compound (~60 % of total PFAS). The detected levels were significantly below regulatory limits, with dietary intake estimates remaining within EFSA's TWI (EFSA, 2020). However, maximum concentration scenarios suggested intake could reach 45 % of the threshold. Spatial distribution analysis indicated multiple contamination sources, highlighting potential localized hotspots within Latvia. On the other hand, Sapozhnikova et al. (2025) analyzed 35 PFAS in brown trout and mottled sculpin from East Canyon Creek, Utah, USA. Twenty PFAS were detected, with $\sum$20PFAS levels ranging up to 63.9 ng/g in sculpin and 52.1 ng/g in trout. PFOS was the predominant compound, although no significant biomagnification was observed. PFDA and FOSA were the most frequently detected PFAS. Risk assessment based on EFSA guidelines showed that 74 % of sculpin and 45 % of trout samples exceeded at least one maximum level. Estimated weekly intake calculations suggested that consuming 4.2–5.6 meals per week could meet the EFSA's tolerable intake threshold (EFSA, 2020).

2.1.1. Recent reviews on the topic

Giffard et al. (2022) highlighted methodological inconsistencies in PFAS studies, particularly for shellfish. Geographic, species-specific, and habitat-driven variability in PFAS levels, coupled with limited bioaccumulation data, complicates risk assessments. The authors urged the use of standardized sampling protocols, expanded global monitoring, and targeted advisories for shellfish from industrial or aqueous film-forming foam (AFFF)-impacted sites. In turn, Pasecnaja et al. (2022) emphasized PFAS persistence in food chains, identifying fish, eggs, and fruits as major dietary sources. According to the authors, while EFSA's 2020 TWI aims to mitigate risks, analytical methods often lack sensitivity for precise compliance monitoring. On the other hand, Torres and De-la-Torre (2023) synthesized global contamination patterns, noting elevated PFAS levels in freshwater species due to limited dilution in lentic ecosystems. Proximity to industrial sites strongly correlates with contamination, with legacy PFAS dominating despite phase-outs. Short-chain PFAS emerged as understudied threats, warranting urgent toxicological and environmental research. Langberg et al. (2024) compared EU and the USA PFAS regulations, analyzing wild and farmed fish from diverse regions. While most PFOS levels fell below the EU's environmental quality standard, even moderate fish consumption exceeded health-based thresholds. The study stressed challenges in harmonizing risk communication amid evolving safety guidelines. Recently, Petali et al. (2024) reviewed US fish consumption advisories (FCAs), which lack federal PFAS-specific guidance. State-derived PFOS thresholds vary widely, complicating risk communication. The authors called for standardized methods, mixture toxicity assessments, and community-engaged approaches to address evolving analytical and toxicological uncertainties.

2.2. Animal-origin food – Livestock, poultry products, and milk

Recent research has significantly advanced the understanding of PFAS in animal-derived foods, revealing critical insights into contamination pathways, species-specific bioaccumulation patterns, and human health risks. The distribution of PFAS in animal tissues is influenced by multiple factors. Environmental drivers include proximity to industrial emissions, wastewater discharges, contaminated feed, and polluted irrigation water, all of which contribute to elevated levels in livestock and poultry (Domingo & Nadal, 2017). Physiological characteristics also play a key role: PFAS bind preferentially to proteins rather than lipids, leading to accumulation in the blood, liver, and kidneys. The chain length and functional group determine tissue partitioning and elimination rates (EFSA, 2020). Species-specific differences in metabolism and excretion further modulate internal concentrations, with aquatic organisms and egg-laying species showing particularly high burdens. It has been demonstrated that PFAS distribution varies by environmental factors and animal physiology, with higher risks observed for vulnerable populations through aquatic products and eggs. Regulatory compliance generally remains adequate; however, specific scenarios, such as proximity to industrial sites or certain farming practices, pose elevated concerns regarding exposure. A summary of studies on PFAS concentrations in various food groups, excluding fish and shellfish, is presented in Table 2 and discussed below.

Xing et al. (2016) conducted a review of PFAS levels in animal-derived foods, identifying environmental and biological factors influencing contamination. Linear long-chain PFAS, particularly PFOA and PFOS, dominated the environmental media, with suspended particulates and microbial activity modulating their distribution. Protein-rich tissues showed higher PFAS accumulation, driven by species-specific transport proteins. Carnivorous fish exhibited greater bioaccumulation than omnivores, while poultry metabolized PFAS faster than mammals. Food processing and packaging materials, especially high-fat products, further contributed to contamination. The study highlighted elevated health risks for women and children consuming aquatic products, underscoring the need for targeted food safety interventions. Regarding the influence of maternal diet on PFAS transfer, Wang et al. (2017) analyzed dietary predictors of PFAS in maternal plasma and breast milk within the New Hampshire Birth Cohort (USA). Using adaptive elastic net regression and multivariable models, the authors linked higher fish, egg, coffee, and white rice intake during pregnancy to elevated PFOS, PFOA, and PFDA levels. For instance, each standard deviation increase in egg consumption raised plasma PFOS by 4.4 % and milk PFOA by 12.4 %. These findings highlight maternal diet as a key pathway for PFAS exposure, providing valuable insights for public health strategies to reduce prenatal transfer. Expanding the scope to livestock health impacts, Death et al. (2021) reviewed data on PFAS transfer in livestock and game animals. Small-scale studies in cattle, pigs, and poultry identified no overt health effects except in poultry, where metabolic disruptions were noted. Livestock products showed lower PFAS levels compared to game tissues, although data gaps persisted for hunted species. That review emphasized the need for longitudinal studies to assess chronic toxicity and refine exposure guidelines. To assess human exposure risks, Liu, Nordstrom, et al. (2022) measured PFAS in raw milk and cow feed from nine Chinese provinces. Milk concentrations ranged from below detection limits to 9.82 ng/g dw (average: 1.03 ng/g dw), while feed ranged from 0.99 to 144 ng/g dw (average: 7.68 ng/g dw). PFBA dominated in feed (34.0 %), and PFOS prevailed in milk (67.5 %). Although no clear correlation emerged between paired feed and milk samples, feed near fluorination plants had higher PFAS concentrations, which were reflected in elevated levels in milk. Risk assessments revealed hazard quotients exceeding one for adults and children under the strictest reference doses, with children at greater risk via milk consumption.

In Poland, Mikolajczyk et al. (2023b) quantified 14 PFAS in 73 milk samples from cows, goats, and sheep. Sheep's milk had the highest ∑4PFAS (0.0055 ng/g), followed by goat (0.0046 ng/g) and cow milk (0.0008 ng/g). Linear PFOS detection frequencies ranged from 33 % (cow) to 93 % (sheep). Estimated intakes for children (0.153–0.266 ng/kg bw) and adults (0.050–0.88 ng/kg bw) remained below 7 % and 2 % of EFSA's TWI (EFSA, 2020), respectively, indicating minimal risk from Polish dairy consumption. In parallel, Xiao et al. (2024) investigated PFAS in cow feed, water, and milk across 20 Chinese regions. Feed contained PFPeA (2.28 ng/g), water had PFOA (4.80 ng/L), and milk showed PFOA dominance (51.5 % of ∑PFAS). Carry-over rates were highest for PFOS (29.58 %) and PFOA (15.78 %). Risk assessments identified Central China's 1-year-olds as exceeding EFSA's RfD for PFOA, highlighting regional disparities in exposure from milk. On the other hand, Wilson et al. (2021) exposed laying hens to PFAS-contaminated water, establishing linear correlations between water and egg concentrations. Hens consuming water below Australian safety limits (PFOS: 0.07 ng/L; PFOA: 0.56 ng/L) produced eggs within Food Standards Australia New Zealand thresholds. Post-exposure, PFAS residues declined rapidly, supporting regulatory benchmarks for safe egg production.

Gazzotti et al. (2021) monitored PFAS contamination in Italian eggs, comparing backyard chicken eggs to those from commercial laying hens. The results indicated a relatively consistent PFAS contamination across backyard chicken eggs, with PFOS being the most prominent compound. PFAS concentrations were significantly higher in eggs from backyard chickens compared to commercial eggs, which aligns with previous findings in Italy. Gazzotti et al. (2021) estimated that consuming eggs from backyard chickens could contribute significantly to dietary PFAS intake, potentially reaching up to 29 % of the TWI for children, based on EFSA's established TWI limit. This highlighted the potential for eggs from backyard chickens to be a notable source of PFAS exposure.

Shifting focus to environmental proximity, Lasters et al. (2022) analyzed eggs from gardens near a Belgian fluorochemical plant, detecting PFOS (up to 241 ng/g) and PFOA universally. Contamination decreased with distance, while hens fed kitchen scraps exhibited higher levels than commercial-fed counterparts. Two eggs weekly exceeded EU health guidelines in 67 % of locations, underscoring risks from self-cultivated foods near industrial zones. In turn, regarding production systems and egg contamination, Mikolajczyk et al. (2022) found organic eggs most contaminated (∑4PFAS: 0.10 ng/g). PFOS constituted 37–100 % of contaminants, with children's intake reaching 15 % of TWI. Free-range and cage eggs showed lower levels, linking farming practices to exposure variability. The same research group (Mikołajczyk et al., 2024) measured PFAS content in chicken eggs, cow, and horse livers, from various regions of Poland. The mean lower bound (LB) of the four PFAS (PFOS, PFOA, PFNA, and PFHxS) concentrations were highest in cow livers (0.52 ng/g) and much lower in chicken (0.17 ng/g), and horse livers (0.13 ng/g) and chicken eggs (0.096 ng/g). The ratio of the sum of the four PFAS to the limits set by Commission Regulation (EU) 2023/915 was <7 % for liver and < 6 % for eggs. Linear PFOS was the compound with the highest detection frequency (8 % in eggs and 48 % in all livers). The study estimated that dietary exposure to the sum of the four PFAS via consumption of liver tissue from farm animals accounted for less than 52 % of the TWI for children and less than 17 % for adults, while dietary intake via an average portion of three eggs led to a low exposure of less than 15 % for children and less than 5 % for adults. Also addressing contamination sources, Granby et al. (2024) traced PFAS in Danish organic eggs to fishmeal additives, revealing ∑4PFAS up to 2.62 ng/g. Children's exposure (10.4 ng/kg bw) exceeded EFSA's TWI by 236 %. Removing fishmeal reduced PFAS within weeks, demonstrating feed management's efficacy in mitigating contamination. Surma et al. (2023) determined the levels of 10 PFAS in various food types in Poland, focusing on protein-rich items such as fish, meat, liver, eggs, and legumes. The analysis revealed that PFOA was the most frequently detected PFAS present in 84 % of the food samples. The maximum concentration of PFOA was 0.50 ng/g, found in a herring sample. The highest concentrations among all PFAS were observed for PFBA (35 ng/g in pork liver) and PFOS (12 ng/g in herring).

The above studies have delineated PFAS pathways from the environment to the food chain, emphasizing species-specific accumulation, dietary influences, and proximity to industrial sources. While regulatory standards generally ensure safety, targeted interventions —such as modifying livestock feed and monitoring high-risk regions —are critical to protecting vulnerable populations. Future research should prioritize longitudinal health assessments in animals and humans to refine exposure thresholds.

2.3. *Plant-based food*

Yang et al. (2023) analyzed PFAS in various grocery store foods collected in the USA, detecting PFAS at concentrations ranging from 0.01 ng/g (PFBS in washed green beans and PFHxA in unwashed tomato) to 2.68 ng/g (PFHxS in radish) on a dry weight basis. The concentrations of PFOA in carrots, lettuce, radish, and canned green beans resulted in median exposure intake (EI) values of 0.016–0.240 ng/kg bw/day, surpassing the EPA's reference dose (RfD) of 0.0015 ng/kg bw/day. Washing reduced radish PFOA concentrations below the detection limit, but the EIs at the reporting limit still exceeded the RfD. On the

Table 2
Summary of Studies on PFAS Concentrations in various Food Groups.*

Country/Region/ City	Specific Food Items Analyzed	Main Results (Concentrations)	Highlights	Reference
USA (New Hampshire)	Maternal diet (fish, eggs, coffee, rice)	Egg intake raised plasma PFOS by 4.4 %, milk PFOA by 12.4 % per SD increase	Maternal diet drives PFAS transfer to breast milk; fish and eggs key exposure pathways	Wang et al. (2017)
Global (Review)	Livestock, game animals, poultry	Lower PFAS in livestock products vs. game; poultry showed metabolic disruptions	Data gaps for hunted species; need for chronic toxicity studies	Death et al. (2021)
China (9 provinces)	Raw milk, cow feed	Milk: <DL to 9.82 ng/g dw (avg: 1.03 ng/g); Feed: 0.99–144 ng/g dw (avg: 7.68 ng/g); PFOS 67.5 % in milk	Higher PFAS near fluorination sites; children at higher risk (HQ > 1)	Liu et al. (2022a)
Poland	Milk (cow, goat, sheep)	Sheep: 0.0055 ng/g, Goat: 0.0046 ng/g, Cow: 0.0008 ng/g (∑4 PFAS); PFOS detection 33–93 %	Minimal risk; intake <7 % TWI (children), <2 % (adults)	Mikolajczyk et al. (2023b)
China (20 regions)	Cow feed, water, milk	Feed: PFPeA 2.28 ng/g; Water: PFOA 4.80 ng/L; Milk: PFOA 51.5 % of ∑PFAS	Central China 1-year-olds exceed PFOA RfD; high carry-over for PFOS (29.58 %)	Xiao et al. (2024)
Australia	Eggs (laying hens)	Linear correlation between water PFAS and egg levels; PFOS <0.07 ng/L, PFOA <0.56 ng/L in water	Eggs within safety limits; PFAS declined post-exposure	Wilson et al. (2021)
Italy	Eggs (backyard vs. commercial hens)	PFOS dominant; higher in backyard eggs (up to 29 % TWI for children)	Backyard eggs a significant PFAS source compared to commercial	Gazzotti et al. (2021)
Belgium	Eggs (near fluorochemical plant)	PFOS up to 241 ng/g; PFOA universal; decreased with distance	67 % locations exceed EU guidelines with 2 eggs/week; kitchen scraps increase levels	Lasters et al. (2022)
Poland	Eggs (organic, free-range, cage)	Organic: ∑4 PFAS 0.10 ng/g; PFOS 37–100 %; children's intake 15 % TWI	Organic eggs most contaminated; farming practices affect exposure	Mikolajczyk et al. (2022)
Poland	Chicken eggs, cow/ horse livers	Cow liver: 0.52 ng/g, Eggs: 0.096 ng/g (∑4 PFAS); PFOS detection 8 % (eggs), 48 % (livers)	Exposure <52 % TWI (children), <17 % (adults) for liver; <15 % (children) for eggs	Mikolajczyk, Warenik-Bany, Pajurek and Marchand (2024)
Denmark	Organic eggs	∑4 PFAS up to 2.62 ng/g; children's exposure 10.4 ng/kg bw (236 % TWI)	Fishmeal in feed drives contamination; removal reduces PFAS	Granby et al. (2024)
Poland	Fish, meat, liver, eggs, legumes	PFOA in 84 % samples (max 0.50 ng/g in herring); PFBA 35 ng/g (pork liver); PFOS 12 ng/g (herring)	Protein-rich foods key PFAS sources; PFOA most frequent	Surma et al. (2023)
USA	Grocery store foods (beans, tomato, etc.)	0.01 ng/g (PFBS in beans, PFHxA in tomato) to 2.68 ng/g (PFHxS in radish)	PFOA in carrots/lettuce exceeds EPA RfD; washing reduces radish PFAS	Yang et al. (2023)
China	Grains (soybeans, rice, wheat, maize)	Soybeans: 1.01 ng/g, Rice: 0.570 ng/g; PFBA, PFOA dominant	Eastern China higher due to industry; intake 0.0829–3.32 ng/kg bw/day	Li et al. (2024)
Australia (Sydney/ Newcastle)	Fruits, vegetables	PFOA: 0.038–1.996 ng/g fw (7 samples); PFOS: 0.132–0.911 ng/g fw (2 samples)	Girls aged 4–8 most vulnerable; exposure < Australian safety limits	Liu et al. (2024)
Poland	Fruits, vegetables (local & imported)	PFBA: max 50.740 ng/g (banana/orange/apple); PFOA most frequent	Low detection (<10 %); origin impacts PFAS distribution	Sznajder-Katarzyńska et al. (2018)
Global (method development)	Fruits, vegetables	PFOA, PFHpA, PFHxA in leafy vegetables; detection limit 0.5 ng/g	Leafy vegetables primary PFAS source; method achieves 90–119 % recovery	Kause et al. (2024)

ABBREVIATIONS
6:2 Cl-PFESA – 6:2 Chlorinated polyfluorinated ether sulfonate
6:2 diPAP – 6:2 Fluorotelomer phosphate diester
6:2 FTS – 6:2 Fluorotelomer sulfonate
6:2 monoPAP – 6:2 Fluorotelomer phosphate monoester
BAF – Bioaccumulation Factor
br-PFOA – Branched-perfluorooctanoic acid
br-PFOS – Branched-perfluorooctanesulphonate
BW – Body weight
EDI – Estimated Daily Intake
EFSA – European Food Safety Authority
EU – European Union
FCMs – Food contact materials
HFPO-DA – Hexafluoropropylene oxide-dimer acid
HR – Hazard ratios
L-PFOS – Linear-perfluorooctanesulphonate
LOD – Limit of detection
LOQ – Limit of quantification
Minor F53B – 11-Chloroeicosafluoro-3-oxaundecane-1-sulfonic acid (11Cl-PF3OUdS)
MPAH – 2-(N-methyl-PFSOA)-acetato
NHANES – National Health and Nutrition Examination Survey
OBS – Sodium p-perfluorous nonenoxybenzene sulfonate
PFAA – Perfluoroalkyl acid
PFAS – Per- and polyfluoroalkyl substances
PFBA – Perfluorobutanoic acid
PFBS – Perfluorobutanesulphonate
PFCA – Perfluoroalkyl carboxylic acids
PFDA – Perfluorodecanoic acid
PFDE – Perfluorodecanoic acid
PFDS – Perflurodecanesulphonate
PFDoA – Perfluorododecanoic acid

PFDoDS – Potassium perfluoro-1-dodecanesulfonate
PFHpS – Perfluoroheptanesulfonate
PFHxA – Perfluorohexanoic acid
PFHxS – Perfluorohexanesulphonate
PFNA – Perfluorononanoic acid
PFOA – Perfluorooctanoic acid
PFOSA, FOSA – Perfluorooctanesulfonamide
PFOS – Perfluorooctanesulphonate
PFC – Perfluorinated compounds
PFPeA – Perfluoropentanoic acid
PFPeS – Perfluoropentanesulfonate
PFSA – Perfluoroalkyl sulfonic acids
PFTrDA – Perfluorotridecanoic acid
PFTrDS – Perfluorotridecanesulfonic acid
PFTeDA – Perfluorotetradecanoic acid
PFuDA, PFUnDA – Perfluoroundecanoic acid
PreFOS – PFOS-related precursor
QuEChERS – Sample preparation method – Quick, easy, cheap, effective, rugged, and safe
RfD – Reference dose
TDS – Total Diet Study
TWI – Tolerable weekly intake
US.EPA – United States Environmental Protection Agency
US.FDA – United States Food and Drug Administration
dw – Dry weight
ww – Wet weight

[*] The list of abbreviations is shown in the order they appear in the text, starting with the PFAS, with other abbreviations also used.

other hand, Li et al. (2024) analyzed PFAS contamination in raw grains from major grain-producing regions in China. Sixteen PFAS were detected across different grain types, with soybeans exhibiting the highest total PFAS levels (1.01 ng/g), followed by rice (0.57 ng/g), wheat (0.54 ng/g), and maize (0.25 ng/g). Short-chain PFCAs were detected more frequently than long-chain variants. PFBA and PFOA dominated wheat, maize, and soybeans, while sodium p-perfluorous nonenoxybenzene sulfonate (OBS) was prevalent in rice. Eastern China showed higher contamination levels, which were attributed to industrial activity. Daily intake estimates ranged from 0.0829 to 3.32 ng/kg bw/day. In turn, Liu et al. (2024) assessed 30 PFAS compounds in 53 fruit and vegetable samples from the Australian Sydney and Newcastle markets. PFOA was found in 7 samples (0.038–1.996 ng/g ww), while PFOS appeared in only two samples (0.132–0.911 ng/g ww). PFHxS was not detected. Daily intake calculations showed girls aged 4–8 years were most vulnerable, although exposure levels remained below Australian safety thresholds, representing 1.3 % of tolerable PFOA intake and 9.9 % for PFOS. In Poland, Sznajder-Katarzyńska et al. (2018) conducted a study aimed at examining 10 PFAS in locally grown and imported fruits and vegetables. Only three compounds (PFBA, PFOA, PFOS) were quantifiably detected, with less than 10 % detection frequency across 55 samples. PFBA showed the highest concentration (50.740 ng/g) in banana, apple, and orange samples. PFOA was the most frequently detected compound, with origin and growing region potentially influencing PFAS distribution. More recently, Kause et al. (2024) developed an improved method to detect 20 PFAS compounds at sub-parts-per-trillion levels in fruits and vegetables. The method achieved recovery rates of 90–119 % and detection limits of 0.5 ng/g. Testing 215 samples from local stores, leafy vegetables were found to be the primary source of PFAS exposure, particularly PFOA, PFHpA, and PFHxA. In Poland, Sznajder-Katarzyńska et al. (2020) developed a reliable method for detecting ten perfluoroalkyl acids in complex fatty matrices like fats and oils. PFOA was the most frequently detected compound (100 % occurrence), while PFBA showed the highest concentrations. The estimated exposure to PFOA reached 46 % of the EU's TWI and 19 % for the Polish population, highlighting a potential health risk.

Plant-based foods generally contain lower PFAS concentrations compared to animal-derived products. This difference is explained mainly by bioaccumulation processes, as PFAS tend to bind to proteins in blood and liver rather than to lipids, leading to higher concentrations in animals and biomagnification through the food chain (Death et al., 2021; Xing et al., 2016). While plants can absorb PFAS from contaminated soil and irrigation water, their uptake is usually lower, and distribution varies by chain length, with short-chain PFAS being more mobile and more likely to accumulate in edible plant tissues (Yang et al., 2023). Consequently, dietary exposure is typically greater from fish, shellfish, eggs, and dairy products, while plants contribute to a lesser extent unless grown in highly contaminated environments.

2.4. Processed food and packaging transfer of PFAS

Regarding packaging, Susmann et al. (2019b) examined links between PFAS levels and dietary habits using NHANES data (2003–2014). Higher serum PFAS concentrations were generally associated with the consumption of fast food, restaurant meals, and microwave popcorn. Popcorn consumption showed the strongest correlation, with PFDA levels increasing by up to 63 % in frequent consumers, likely due to PFAS migration from packaging. In contrast, home-cooked meals were inversely associated with PFAS exposure, suggesting reduced contact with food contact materials containing these substances. Several studies have reported PFAS in a variety of food packaging, particularly grease-resistant paper and cardboard used for fast foods such as burger wrappers, pizza boxes, and French fry containers, as well as microwave popcorn bags and nonstick cookware. These applications rely on PFAS for their oil- and water-repellent properties, which may result in migration into food under certain conditions (Ramírez Carnero et al., 2021). They highlighted factors influencing PFAS migration from food contact materials (FCMs) into food. Their findings emphasized the need to understand these conditions to assess potential exposure risks and improve food safety measures. Sapozhnikova et al. (2023) investigated PFAS in 88 food packaging samples, finding detectable levels in 84 % of samples. The 6:2 fluorotelomer phosphate diester (6:2 diPAP) was the most common, showing high detected levels (224 ng/g). Migration experiments showed increasing PFAS transfer over 10 days, although weekly intake estimates remained below EFSA safety thresholds. On the other hand, Van Leeuw et al. (2024) reported PFPeA contamination in Belgian chocolate from greaseproof wrapping papers, while Di Mario et al. (2024) examined 110 food contact materials, including paper, board, and plant-based alternatives. Eleven out of 25 targeted PFAS were detected, mainly perfluoroalkyl carboxylic acids. All paper analogue samples contained PFAS, with 43 % of paper/board samples showing contamination. Risk assessment identified potential concerns with coffee cups and food trays (Di Mario et al., 2024). On the other hand, Huang et al. (2022) analyzed 27 PFAS in fast food samples, detecting notable levels in ice cream, instant noodles, and bubble tea. PFOA, PFBA, and 6:2 monoPAP were found at relatively high concentrations. PFAS migration from bubble tea cups differed between food simulants and actual bubble tea matrices. Storage conditions significantly impacted PFAS levels, with long storage times increasing concentrations up to 4.8 times and high temperatures up to 7.3 times. The calculated hazard ratio suggests that PFAS exposure from bubble tea consumption was a potential health concern.

3. PFAS and human dietary exposure assessment

Papadopoulou et al. (2017) assessed human exposure to PFAS through the diet in Norway using three methods: a 1-day duplicate diet study, a 2-day weighted food diary, and a Food Frequency Questionnaire (FFQ). The study found that PFOS and PFOA were the most abundant PFAS in the diet. High intakes of fats, oils, and eggs were linked to higher PFOS and PFOA intakes from solid foods, while milk and alcoholic beverages were linked to higher PFOA intakes from liquid foods. The study provided evidence that food diary or FFQ-based methods could offer comparable intake estimates to those derived from duplicate diet studies. On the other hand, Costopoulou et al. (2022) evaluated PFAS intake from fish, eggs, and drinking water in Greece. The study found that fish and eggs contributed significantly to PFOS and PFOA dietary intake, with mean weekly intake estimates exceeding the TWI proposed by EFSA (2020). The need for continuous monitoring of PFAS levels in food and efforts to reduce these levels to protect public health was emphasized. The Human Biomonitoring for Europe (HBM4EU, 2017–2022) conducted a comprehensive investigation of PFAS exposure and health effects in Europe. The study synthesized human biomonitoring data, developed a Quality Assurance/Quality Control Program, and conducted aligned human biomonitoring studies. The results showed that 14.3 % of European teenagers had serum PFAS levels exceeding EFSA's guideline value. The study highlighted the importance of monitoring PFAS exposure in specific workplaces and environmental hotspots and supported the restriction of the entire PFAS group. In turn, Abafe et al. (2021) measured PFAS concentrations in farmed marine shellfish in South Africa to determine human daily intake and hazard quotient. The estimated daily intake for Σ10PFAS through shellfish consumption ranged from 0.05 to 1.58 ng/kg bw/day, with low hazard quotients indicating no significant health risk. The study noted regional disparities in exposure and emphasized the need for standardized sampling techniques and methodologies for better comparison of PFAS data.

On the other hand, Giffard et al. (2022) reviewed PFAS occurrence in shellfish, noting variability in concentrations by geographic location, species, habitat, and PFAS compounds. The review identified opportunities for standardizing sampling techniques and methodologies to improve the comparability of PFAS data. The potential risks to frequent shellfish consumers from sites with aqueous film-forming foam (AFFF) and industrial contamination were highlighted, while further research to inform health-protective policies was suggested. Liu, Zhang, et al. (2022) showed that fish consumption from the Great Lakes Basin was linked to increased PFAS levels, particularly PFOS, in licensed anglers and Burmese refugees in western New York. Blood samples showed PFOS concentrations up to six times higher than the US general population. Frequent fish consumption correlated with elevated serum PFAS, with potential ethnic differences in exposure among the Burmese. It was concluded that additional research and outreach efforts were needed to raise awareness and minimize contaminant exposure in these populations. In turn, Hamade (2024) reviewed epidemiology studies on PFAS-associated noncancer health indicators used by the US.EPA to develop reference doses (RfDs) for PFAS. The review compared these health outcomes with those associated with seafood intake, finding that the benefits of fish consumption generally outweigh the risks of PFAS exposure. The study discussed approaches for risk assessors and policymakers to develop fish consumption recommendations considering PFAS exposure.

4. Health implications and risk assessment of dietary exposure to PFAS

4.1. Influence of cooking

In 2008, we conducted the first study on the effects of cooking foods on human exposure to 11 PFAS (Jogsten et al., 2009). Composite samples of veal steak (raw, grilled, and fried), pork loin (raw, grilled, and fried), chicken breast (raw, grilled, and fried), and chicken nuggets (fried) were analyzed. The results of that study were inconclusive regarding whether cooking with non-stick cookware increases or reduces human exposure to PFAS. No definitive, clear data on the effects of cooking on PFAS levels were found in our previous reviews on human dietary exposure to PFAS (Domingo, 2012; Domingo & Nadal, 2017). Next, we summarized the most relevant details on the studies about the topic published since our last review (Domingo & Nadal, 2017).

Taylor et al. (2019) conducted one of the systematic investigations into how boiling, frying, and baking could alter PFAS concentrations in seafood harvested near a known PFAS point source and a reference location. The analysis of 23 PFAS compounds revealed PFOS as the most frequently detected contaminant, with concentrations in School Prawn doubling after boiling and increasing in Dusky Flathead during baking, likely due to mass loss during cooking. Notably, boiling halved PFHxS and PFOA levels in Blue Swimmer Crab, but no cooking method consistently reduced PFAS exposure across all species, challenging assumptions about thermal mitigation. In turn, Hu et al. (2020) expanded this question by comparing boiling, steaming, grilling, and frying grass carp from Tangxun Lake, China. That study identified PFOS as the dominant PFAS (59.6–136 ng/g ww) in raw fish, with long-chain PFAS increasing post-cooking while short-chain variants like PFBS migrated into cooking juices. Boiling was a relatively safer method, as it slightly reduced total PFAS intake while concentrating PFOS in fillets. However, consuming the cooking juices increased PFBS exposure risks. The study highlighted the nuanced trade-offs between cooking techniques and PFAS redistribution. On the other hand, Vendl et al. (2022) conducted a meta-analysis of various studies, revealing an average 29 % PFAS reduction through cooking despite extreme variability. Their multilevel analysis showed that extended cooking times, higher liquid-to-tissue ratios, and shorter PFAS carbon chains (in oil-based cooking) enhanced reductions while cooking temperature alone lacked significant impact. Although promising, the study cautioned that complete PFAS elimination would require impractical cooking durations, underscoring the need for balanced kitchen guidelines. In China, Chen et al. (2023) shifted focus to biomagnification dynamics in South China Sea species, finding trophic magnification (TMF >1) for PFOS and F—53B in marine food webs. The cooking experiments demonstrated divergent outcomes: baking increased ΣPFAS concentrations in most organisms, while boiling and frying reduced absolute amounts, suggesting method-dependent outcomes. Despite these variations, health risk assessments indicated low exposure threats from cooked seafood, providing crucial quantitative benchmarks for dietary safety. On the other hand, Sun et al. (2023) examined PFAS distribution in squids from China's coastal regions, identifying higher contamination in subtropical zones (15.90 ng/g dw vs. 11.77 ng/g dw). Cooking transferred PFAS to juices and oils, prompting recommendations to discard these byproducts. Notably, hazard ratio assessments flagged PFPeA as a high-risk compound, contrasting with squids' beneficial fatty acid profile, thus advocating for optimized processing techniques to balance nutrition and contaminant reduction. Also, in China, Zhao et al. (2023) introduced bioaccessibility as a critical factor, using in vitro simulations to show steaming reduced PFAS bioavailability (26.0–108.1 %) more effectively than frying, likely through protein aggregation during heat treatment. The authors found that gastric lipase enhances long-chain PFAS release during digestion, revealing complex interactions between cooking methods, lipid metabolism, and contaminant absorption, emphasizing the need for method-specific risk evaluations.

In another order of things, Zhang and Tang (2024) analyzed NHANES data from 11,137 participants, identifying significant inverse associations between low-salt diets/salt-free cooking and serum PFOS, PFOA, PFHxS, PFDA, and PFNA levels. Regular salt use during food preparation correlated with elevated PFAS concentrations, suggesting dietary sodium management as a potential exposure mitigation strategy. While requiring further validation, these findings open new avenues for public health interventions targeting cooking habits alongside food processing reforms. Future research could examine how reducing the use of processed and packaged foods high in both sodium and PFAS might lower exposure, as well as explore interventions promoting fresh, home-prepared meals with less reliance on grease-resistant packaging. Additionally, public health strategies could involve reformulating food packaging to eliminate PFAS-based coatings while maintaining functionality, thereby combining nutritional and toxicological benefits. Moreover, given the correlational nature of these findings, further mechanistic and longitudinal studies are needed to clarify whether sodium intake directly influences PFAS toxicokinetics or merely reflects dietary patterns linked to processed food consumption. This distinction is essential to guide evidence-based recommendations. Importantly, as a potentially low-cost and widely scalable strategy, dietary sodium management could hold particular promise in low- and middle-income countries, provided it is supported by public health policies that promote access to fresh foods and reduce dependency on processed products.

4.2. Health Risk

The growing body of research on PFAS reveals escalating concerns about their health risks through dietary and environmental exposure pathways. Christensen et al. (2017) identified seafood consumption as a significant source of PFAS exposure in the US population, with PFOS and PFOA dominating serum profiles (medians: 8.3 ng/mL and 2.7 ng/mL, respectively). Shellfish intake correlated with elevated levels of most PFAS, while tuna and salmon specifically increased PFDA and PFuDA. These findings highlighted dietary routes as critical vectors for bioaccumulation, even at low consumption frequencies (median 1.2 fish meals/30 days), underscoring risks for populations with sustained seafood intake. Zhou et al. (2019) examined the relationship between plasma PFAS concentrations and dietary intake in reproductive-aged women in Shanghai, China. The researchers measured ten PFAS in plasma samples from 933 women and collected dietary information through questionnaires. After adjusting for potential confounders, a higher frequency of aquatic product consumption (freshwater fish, marine fish, shellfish, shrimp, and crab) was significantly associated with increased concentrations of PFOS, PFOA, PFNA, PFDA, PFuDA, and PFDoA. Freshwater fish intake showed the strongest positive association with PFAS levels. Conversely, soy product consumption was associated with lower concentrations of PFDA, PFuDA, PFNA, PFOS, and PFDoA. Drinking bottled water, compared to tap water, was associated with significantly lower blood levels of PFHpA, PFDA, PFOA, PFuDA, and PFBS. On the other hand, the HBM4EU Aligned Studies (Uhl et al., 2023) expanded these insights to European teenagers, revealing that 14.3 % exceeded the EFSA's safety threshold of 6.9 μg/L for combined PFAS exposure. Regional disparities were stark: Northern/Western European adolescents showed 24 % exceedance rates, triple those in Southern/Eastern regions, primarily due to contaminated drinking water and foods like fish, eggs, and offal. Occupational exposures further compounded risks, with chrome plating workers exhibiting extreme serum PFAS levels (P95: 192 μg/L), emphasizing the dual burden of environmental and workplace contamination. This continental-scale evidence underscored the urgency of EU-wide PFAS restrictions and environmental remediation to mitigate endocrine-disrupting effects linked to developmental and immune dysfunction (Uhl et al., 2023). In turn, mechanistic research by Xing et al. (2023) elucidated how PFAS bioaccumulation dynamics vary across species and food chains. Long-chain compounds ($C \geq 7$), particularly those with sulfonic groups, dominated contamination profiles in animal-derived foods due to their persistence in protein-rich tissues like liver and kidney. Carnivorous fish exhibited 3–5× higher PFAS burdens than omnivorous species - a consequence of trophic magnification - while poultry metabolized PFAS faster than mammals, revealing species-specific vulnerabilities. The study also exposed contamination pathways from food packaging, especially in high-fat products, and identified women and children as high-risk groups due to frequent aquatic food consumption linked to developmental toxicity. Concurrently, Wang et al. (2024) bridged these exposure pathways to maternal-fetal health, demonstrating that prenatal diets heavy in fish, eggs, or white rice, increased PFAS transfer to plasma and breast milk. Each additional serving of eggs elevated maternal plasma PFOS (4.4 %), PFOA (3.3 %), and PFDA (10.3 %), while white rice consumption boosted milk PFOS and PFOA by 7.5 % and 12.4 %, respectively, a consequence of PFAS-laden irrigation water infiltrating staple crops. These findings position prenatal nutrition as a critical intervention point for reducing neurodevelopmental and immune risks in infants, as breast milk remains a key exposure route during early life.

Collectively, these studies traced a progression from early population-level exposure documentation to mechanistic insights and maternal health implications. Persistent themes include the dominance of long-chain PFAS in bioaccumulation, seafood-driven exposure disparities, and heightened vulnerabilities for pregnant individuals and children (Papadopoulou et al., 2019). Emerging evidence on short-chain PFAS in water systems and food packaging warrants intensified monitoring, while regional exposure disparities demand tailored regulatory actions. Recent international regulatory evaluations also reinforce these concerns. The US EPA (2023) proposed stringent maximum contaminant levels (MCLs) for PFOA and PFOS in drinking water at 4 ng/L, with hazard index approaches for mixtures of PFNA, PFHxS, PFBS, and HFPO-DA (GenX). Health Canada (2023) established updated drinking water screening values as low as 30 ng/L for PFOS and 200 ng/L for PFOA, reflecting growing evidence of immunotoxicity and developmental effects. Most recently, the Joint FAO/WHO Expert Committee on Food Additives (JECFA, 2024) evaluated PFOS, PFOA, PFNA, and PFHxS, concluding that no safe level of dietary exposure could be established, underscoring the urgency of global risk management measures. Policy priorities must now integrate dietary advisories, occupational safety standards, and large-scale environmental remediation to disrupt PFAS transmission cycles across ecosystems and generations, safeguarding current and future populations from these pervasive contaminants.

4.3. EFSA risk assessments

In 2018, the European Food Safety Authority (EFSA) evaluated human health risks linked to PFOS and PFOA in food. Analyzing 20,019 datasets, EFSA identified significant analytical variability between upper- and lower-bound exposure estimates, with the latter deemed more reflective of true exposure. Major dietary contributors included seafood, meat, and eggs for PFOS, as well as dairy products, drinking water, and seafood for PFOA. Both compounds exhibit prolonged human half-lives (~5 years for PFOS and 2–4 years for PFOA) due to their resistance to metabolism and slow excretion. Health-based guidance values were derived using epidemiological data: PFOS was associated with elevated serum cholesterol in adults and reduced vaccine efficacy in children, while PFOA primarily increased cholesterol and liver enzyme levels. EFSA established a TWI of 13 ng/kg bw for PFOS and 6 ng/kg bw for PFOA, noting widespread population exceedances (EFSA, 2018). In 2020, EFSA expanded its assessment to include four PFAS (PFOA, PFOS, PFNA, and PFHxS), assuming additive toxicity due to shared mechanisms. Lower-bound exposure estimates ranged from 3 to 22 ng/kg bw/week (mean) to 9–70 ng/kg bw/week (95th percentile), with toddlers facing double the exposure of adults. Key dietary contributors included fish and eggs, with fruits also considered. Using immune system effects as the critical endpoint (particularly reduced antibody response in children), EFSA derived a TWI of 4.4 ng/kg bw for the sum of the four PFAS. This threshold accounted for bioaccumulation and aligned with serum biomarker data, yet significant population exceedances persist (EFSA, 2020).

5. Discussion

The present review confirms that PFAS are widespread contaminants in global food systems, affecting seafood, livestock, poultry, milk, eggs, plant-based foods, and processed products. Contamination varies according to environmental factors, bioaccumulation patterns, dietary habits, proximity to industrial activities, and processing practices. Long-chain PFAS, especially PFOS and PFOA, dominate food profiles due to their persistence and bioaccumulative nature. Seafood, particularly shellfish and freshwater fish, stands out as a major exposure pathway, with concentrations often exceeding EFSA's TWI of 4.4 ng/kg body weight/week for four PFAS (EFSA, 2020). For example, studies such as those by Christensen et al. (2017) and Barbo et al. (2023) have highlighted elevated PFAS levels in US populations linked to the consumption of shellfish and freshwater fish, with median concentrations in fillets ranging from 9.5 to 11.8 ng/g, substantially higher than those found in commercial seafood.

Beyond aquatic products, animal-derived foods such as eggs and milk also contribute significantly to dietary PFAS intake, particularly in regions near industrial sources. Lasters et al. (2022) and Granby et al. (2024) demonstrated how proximity to fluorochemical plants and the use of contaminated feed (e.g., fishmeal) drive PFAS levels in eggs, with children's exposure occasionally surpassing 236 % of the TWI. Similarly, Liu et al. (2022a) and Xiao et al. (2024) reported that milk from cows in industrialized regions of China contains elevated levels of PFAS, posing a higher risk to vulnerable populations, such as infants. These findings agree with Wang et al. (2024), who tied maternal dietary patterns, rich in fish, eggs, and rice, to increased PFAS transfer to breast milk, amplifying prenatal and early-life exposure risks.

Although plant-based foods are generally less contaminated, they are still susceptible to PFAS uptake, as demonstrated by Yang et al. (2023) and Li et al. (2024). Vegetables like radishes and grains like soybeans exhibited detectable PFAS levels, often linked to contaminated soil or irrigation water, with intake estimates occasionally exceeding the reference dose. Processed foods and packaging further complicate exposure dynamics, with Susmann, Schaider, Rodgers and Rudel (2019a) and Sapozhnikova, Taylor, Bedi and Ng (2023) identifying fast food and microwave popcorn as notable sources due to the migration of PFAS from contact materials. Cooking methods, explored by Taylor et al. (2019) and Hu et al. (2020), offer mixed outcomes: while boiling may reduce certain PFAS in seafood, baking can concentrate others, suggesting that thermal processing alone cannot reliably mitigate exposure.

Overall, there is currently no universally effective food processing strategy to eliminate PFAS, highlighting the need for preventive measures at earlier stages of the food chain. The current state of the art for reducing PFAS contamination includes minimizing the use of PFAS-containing materials in food packaging and cookware, promoting alternative food contact materials, and developing advanced decontamination technologies such as adsorption, ion-exchange, and thermal treatments for highly contaminated foodstuffs. Additionally, regulatory efforts to limit PFAS production and use remain crucial for long-term mitigation.

On the other hand, health implications are a critical concern, with PFAS linked to immune suppression, developmental toxicity, and metabolic disruptions (EFSA, 2018, 2020; HBM4EU, 2023). Vulnerable populations, including children, pregnant/lactating women, and frequent seafood consumers, face disproportionate risks, as evidenced by regional exceedances of safety thresholds in Europe (HBM4EU, 2023) and China (Zhou et al., 2019). However, Hamade (2024) noted that the nutritional benefits of seafood might outweigh PFAS risks in some contexts, highlighting the need for nuanced risk-benefit assessments. Disparities in exposure, driven by geographic, socioeconomic, and cultural factors, further complicate global management efforts, with Northern/Western Europe, as well as industrialized Chinese regions, showing higher burdens than Southern/Eastern Europe or less-industrialized areas.

PFAS are widespread contaminants in global food systems, yet significant geographic gaps remain in dietary exposure assessments. In particular, data from African regions are extremely scarce, with no systematic evaluations of PFAS concentrations in foodstuffs having been conducted to date, as well as other emerging regions. This lack of evidence may be attributed to limited exploration of dietary sources, insufficient high-performance analytical capacity for PFAS detection, and prioritization of other pressing food safety challenges in the region. Given the high reliance on locally produced seafood and agricultural products in many African countries, the absence of monitoring hampers reliable risk assessments. Addressing this gap requires strengthening laboratory infrastructure, expanding international collaborations, and implementing targeted biomonitoring and food surveillance programs. Such efforts would be essential to establish baseline data and guide evidence-based policies to mitigate PFAS exposure risks in vulnerable populations.

Most studies on PFAS concentrations in food originate from Northern countries, whereas data from the Global South are scarce. Despite this potential risk, food monitoring and dietary exposure assessments in these regions are extremely limited, representing a critical knowledge gap. Moreover, while the European Union and the United States have established specific limits and guidance values for PFAS in food, equivalent regulatory frameworks in many Southern countries are either absent or are still in the early stages of development. The lack of harmonized standards, difficulties in enforcing monitoring, and the resulting delay in addressing public health implications highlight the urgent need for coordinated research efforts, capacity building, and the implementation of effective regulations in the Global South (Giffard et al., 2022; Pasecnaja et al., 2022; Souza et al., 2022).

Although regulatory frameworks are evolving, they struggle to keep up with the diversity and persistence of PFAS. The EFSA's progressive lowering of TWIs (from 13 ng/kg bw/week for PFOS in 2018 to 4.4 ng/kg bw/week for four PFAS in 2020) reflects growing toxicological evidence, yet enforcement remains inconsistent. Petali et al. (2024) and Langberg et al. (2024) have critiqued the lack of harmonized fish consumption advisories and the understudied risks of short-chain PFAS, which are increasingly prevalent due to the phase-out of legacy compounds. These gaps underscore the urgency of standardized analytical methods, as emphasized by Giffard et al. (2022) and Pasecnaja et al. (2022), to ensure the comparability of data and the robustness of risk assessments.

The analytical determination of PFAS in foodstuffs relies predominantly on liquid chromatography coupled to tandem mass spectrometry (LC-MS/MS), which is considered the gold standard due to its high sensitivity and selectivity for both legacy and emerging PFAS (Domingo & Nadal, 2017; Feng et al., 2024; Giffard et al., 2022). High-performance liquid chromatography (HPLC) coupled to high-resolution mass spectrometry (HRMS) is increasingly used to detect a broader range of compounds - screening, including novel fluoroalkylether substitutes, providing structural elucidation and non-targeted screening capabilities. Gas chromatography (GC) has been applied to volatile or derivatized PFAS, although its use in food analysis is limited compared to LC-based approaches. Sample preparation typically involves solid-phase extraction (SPE) with a WAX cartridge (Weak Anion-eXchange) or protein precipitation for animal-derived foods, and QuEChERS-based or ion-pair extraction methods for plant matrices. Despite advances, challenges persist regarding matrix interferences, the detection of short-chain PFAS, and the need for standardized methods to enhance comparability across studies.

6. Conclusions

PFAS contamination is a global challenge permeating all levels of the food system, with seafood, eggs, milk, and plant-based foods serving as key exposure pathways. Long-chain PFAS like PFOS and PFOA remain dominant, although short-chain alternatives are emerging as significant concerns requiring further investigation. While regulatory thresholds like the EFSA's TWI provide critical benchmarks, widespread exceedances, particularly among children and frequent consumers, remark the need for immediate action. Targeted interventions, such as modifying livestock feed (e.g., removing fishmeal), monitoring high-risk regions, and reducing PFAS in food packaging, offer practical steps to lower exposure. Cooking methods show promise but lack consistency as a universal solution. Future research should prioritize longitudinal health studies to refine exposure thresholds, assess mixture toxicity, and elucidate the impacts of short-chain PFAS. Standardized sampling and analytical protocols are essential to address methodological inconsistencies and enable global comparisons. Policy efforts must integrate dietary advisories with environmental remediation, focusing on industrial hotspots and vulnerable populations. By disrupting PFAS transmission cycles through source control, food system management, and public health strategies, risks and safeguarding current and future generations from these persistent contaminants can be mitigated. Despite increasing concern about human exposure to PFAS among regulatory agencies and the scientific community, research in developing regions, particularly Latin America and Africa, remains notably scarce. This knowledge gap is evident in the limited data available, as documented in this review. Moreover, overarching trends reveal that while legacy PFAS still dominate dietary exposure, emerging short-chain compounds are increasingly detected across diverse food groups and regions, yet their toxicological profiles remain poorly characterized. These patterns highlight the urgent need for harmonized global monitoring frameworks and cross-regional collaborations to ensure that future dietary risk assessments adequately capture both established and emerging PFAS threats.

CRediT authorship contribution statement

Marília Cristina Oliveira Souza: Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization. **Jose L. Domingo:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Funding

This research received no external funding.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors of this manuscript (MCOS and JLD) state that they do not have realtionships or activities that may be interpreted as a conflict of interest by the readers.

Data availability

This is a Review article, for which data have been obtained of the literature using PubMed and Scopus

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Food Research International
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DOI: https://doi.org/10.1016/j.foodres.2025.117612

Food Research International 221 (2025) 117612

Contents lists available at ScienceDirect

Food Research International

journal homepage: www.elsevier.com/locate/foodres

Corrigendum

Corrigendum to “Levels of *per*- and polyfluoroalkyl substances (PFAS) in foodstuffs: a review of dietary exposure, health risks, and regulatory challenges” [Food Res. Int. 221 (2025) 117494]

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The authors regret to inform on this error:

In page 9, left column, line 14 from the bottom, where it is written: 0.5 ng/g, it must be 0.5 ng/kg. In Table 2, last row (Global), column “Main Results (concentrations)”, where it is written 0.5 ng/g, it must also be 0.5 ng/kg.

The authors would like to apologise for any inconvenience caused.

DOI of original article: https://doi.org/10.1016/j.foodres.2025.117494.

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https://doi.org/10.1016/j.foodres.2025.117612