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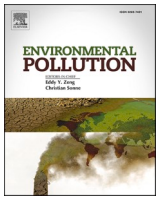

Per- and polyfluoroalkyl substances (PFAS) in food and exposure assessment of the Swedish population☆

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ABSTRACT

In this study, the levels of per- and polyfluoroalkyl substances (PFAS) in food available on the Swedish market were measured, to estimate dietary exposure in different population groups and to compare with the tolerable weekly intake (TWI) established by the European Food Safety Authority (EFSA). In total, 14 PFAS were analysed in food group samples representative for the Swedish market (n = 51) and additional samples (n = 107) of specific foods, including fish and shellfish, meat, eggs, fruits, and vegetables. Dietary exposure was calculated with all detectable PFAS and consumption data from three national dietary surveys of young children, adolescents, and adults. PFAS were observed in 3 of the 17 food groups: eggs, fatty fish, and lean fish. Additional analyses revealed PFAS in all fish and shellfish samples, as well as in wild boar, reindeer, liver pâté, and organic eggs. No quantifiable PFAS were found in fruit, vegetables, conventional eggs, or other meat samples. The intake estimations showed that the median PFAS exposure was below the TWI across all age groups, but up to 19 % of young children, 18 % of adolescents, and 5 % of adults exceeded the TWI. Scenario calculations demonstrated that most of the population, except young children, could safely consume drinking water at the Swedish maximum limit (4 ng Σ4PFAS/L) and fish according to the recommendation (2–3 servings per week) without exceeding the TWI. Approximately 60 % of sum PFAS exposure from food came from Σ4PFAS, emphasizing the need for further risk assessments of other PFAS.

1. Introduction

Per- and polyfluoroalkyl substances (PFAS) are a large group of man-made chemicals that have gained significant attention due to their widespread use and persistence in the environment. These substances have been used since the 1950s in industrial processes and in a wide range of consumer goods (Gluge et al., 2020), and are ubiquitously spread into the environment (Houde et al., 2006; De Silva et al., 2021). Humans are primarily exposed to PFAS through food and drinking water, with additional exposure occurring via dust, air, and the use of PFAS-containing products (Vestergren et al., 2012; Poothong et al., 2020; EFSA, 2020). PFAS enter the food supply chain through various pathways, including uptake from contaminated soil and water, as well as from food packaging and processing during manufacturing (Eze et al., 2024).

Fish have been shown to contribute the most to the exposure to PFAS in food. They contain the highest levels of PFAS among food sources, and their consumption is strongly linked to PFAS intake (Pasecnaja et al., 2022; RIVM, 2023; Langberg et al., 2024; Van Leeuw et al., 2024). Additionally, eggs could be an important source of exposure to humans (Pasecnaja et al., 2022; Bonato et al., 2025). The European Food Safety Authority (EFSA) also recognizes fish, eggs, and, to some extent, fruits as significant sources of PFAS exposure (EFSA, 2020). Recent findings indicate that fruits and vegetables might exhibit relatively high PFAS levels, surpassing meat as a more substantial source of exposure (Pasecnaja et al., 2022).

In 2020, EFSA published a risk assessment of PFAS in food where the previous opinions on perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) were re-evaluated (EFSA, 2008; EFSA, 2018; EFSA, 2020). EFSA established a tolerable weekly intake (TWI),

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for the sum of four PFAS (here after referred as Σ4PFAS), which include, PFOA, perfluorononanoic acid (PFNA), perfluorohexanesulfonic acid (PFHxS), and PFOS. These four PFAS were considered to have similar effects in animals, toxicokinetics, and are also the most common PFAS detected in human blood (EFSA, 2020). The TWI was based on a benchmark dose level (BMDL) of Σ4PFAS in 1-year-old children, derived from the inverse association between Σ4PFAS serum levels and antibody titres against diphtheria. Using a physiologically based pharmacokinetic model, it was estimated that the BMDL in infants corresponds to a maternal intake of 0.63 ng/kg bodyweight (bw)/day for Σ4PFAS and the TWI was established at 4.4 ng Σ4PFAS/kg bw/week (EFSA, 2020). Recent risk assessment indicates that a large portion of the population in Europe exceeds the TWI, and children have approximately twice the level of exposure compared to adolescents and adults (EFSA, 2020).

Given the revised risk assessment from EFSA and the decreasing trends for Σ4PFAS in food and humans (Johansson et al., 2014; Sonnenberg et al., 2023; SFA, 2024a; Gyllenhammar et al., 2025), it is essential to review data on current PFAS levels in food and human exposure. In this investigation, two sets of food samples were analysed: one from the Swedish market basket study and another consisting of specific food types, representing major PFAS exposure sources identified by EFSA. The overall aim of this study was to determine up-to-date concentrations of 14 PFAS in commonly consumed foods, estimate exposure in Swedish young children, adolescents, and adults, and assess potential health risks based on the EFSA TWI.

2. Material and methods

2.1. Food sample collection and preparation

The food items were purchased in food stores in Uppsala, Sweden, mainly in the three major grocery chains covering about 90 % of the market (SFA, 2024a), between September 2022 to March 2023. Since the food distribution system in Sweden is highly centralized, and earlier studies have not shown any clear regional differences (Darnerud et al., 2006), the samples are assumed to be representative of foods at the national level.

The food samples were divided into two parts: one with food group samples from a market basket study and the second with samples of specific foods. The first part consisted of samples collected in the market basket study conducted in 2022 by the Swedish Food Agency. The market basket study resembles a total diet study (World Health Organization et al., 2011) and analyse contaminants as well as nutrients in food groups mirroring the average food consumption of a Swedish citizen (SFA, 2024a). Three samples for each of the 17 food groups were prepared (Supplemental Information (SI) Table S1), with one sample from each grocery chain. The food included in each food group sample and their relative proportions were determined based on a combination of data sources. These included per capita consumption statistics from the Swedish Board of Agriculture, which is based on information on Swedish food production, imports and exports (Swedish board of agriculture, 2021), as well as sales statistics, consumer panel data, and data from Swedish Food Agency's dietary surveys (Riksmaten). The second part, involving specific food samples, was based on food items known to be major sources of PFAS according to EFSA (EFSA, 2020). These specific food samples included fish, meat, eggs, fruits and vegetables, with the majority being fish samples (SI Table S1). Each sample consisted of food from three units, either three different batches of a food item within the same brand, or the same food item from three different brands. The fruit and vegetable samples were mixed with different types of food items included in the same sample (SI Table S1). For the pooled sample, equal amount by weight were taken from each of the three included units.

The food items were stored according to product recommendations prior sample preparation. The inedible parts of the food items such as bone, skin, peels, etc. were removed before sample preparation. The content was further mixed and carefully blended into a homogenate and stored in a freezer prior analyses (−20 °C). The food items were analysed as purchased, without any further preparation (e.g., cooking or frying), except for coffee and tea, which were brewed. The equipment used in the sample preparation were washed with non-perfume detergent and rinsed with acetone to avoid contamination from water. A Retsch GM 300 with a stainless container was used for homogenisation.

2.2. Analytical method

2.2.1. Chemicals and reagents

Native and isotopically labelled PFAS standards included in the targeted analysis were purchased from Wellington Labs (Guelph, Canada). A total of 14 PFAS were targeted in this investigation, including 9 PFCAs (C6−C14), 4 perfluoroalkane sulfonic acids (PFSAs, C4, C6, C8, C10), perfluorooctane sulfonamide (FOSA). Analytical reagent-grade ammonium hydroxide (NH_4OH, 25 %), HPLC- and LC-MS-grade methanol (MeOH, ≥99.8 % and ≥99.9 %, respectively), and HPLC-grade acetonitrile (AcN, ≥99.9 %) were obtained from Fisher Scientific (Ottawa, Canada). Solid-phase extraction (SPE) cartridges used were weak anion exchange (WAX) cartridges (Oasis WAX, 60 mg, 3 mL, 30 μm) from Waters Corporation (Milford, USA). Graphitized carbon (ENVI-Carb™) was purchased from Supelco, Sigma-Aldrich (St. Louis, USA), and LC-MS-grade ammonium acetate was also obtained from Sigma-Aldrich. Laboratory-produced ultrapure water (18.2 MΩ cm) was used throughout the experimental procedures.

2.2.2. Sample preparation

A portion of homogenized sample (SI Table S2) was used for the analysis. Two different extraction methods (solid-liquid extraction or solid phase extraction) were used depending on the food group as indicated in SI Table S2. For the solid food groups, solid-liquid extraction with Envi-Carb clean-up was used. As for liquid samples, solid phase extraction using mixed modes of weak anion exchange cartridge (OASIS, WAX-SPE, 150 mg, 6 mL, Waters) was employed. Details of the methods are provided in the SI.

2.2.3. Instrumental analysis and quantification

An Acquity UPLC system (Waters) equipped with a BEH C18 (100 × 2.1 mm, 1.7 μm particle size, Waters) analytical column was used for all instrumental analyses. Mobile phase A was composed of 2 mM ammonium acetate with the composition of 70 % ultrapure water and 30 % methanol, while mobile phase B was composed of 2 mM ammonium acetate in methanol at a flowrate of 0.3 mL/min. SI Table S4 shows the mobile phases and gradient programme for the analysis. The UPLC system was coupled to a Xevo TQ-S triple quadrupole mass spectrometer (Waters), which was operated in negative ion electrospray ionization (ESI-) mode. Details of the MS parameters and optimized cone-voltages and collision energies for each compound are provided in SI. Multiple reaction monitoring (MRM) was used to improve selectivity, and at least two transitions were monitored for most analytes.

2.2.4. Quality assurance and quality control measures

Two procedural blanks and two in-house QC samples (fish spiked with 1 ng of native standards) were analysed alongside each batch to assess potential contamination and evaluate method repeatability. Since not all PFAS had corresponding mass-labelled internal or recovery standards, accuracy and precision were evaluated by spiking native compounds (1 ng) into each matrix in triplicate. All samples were spiked with available mass-labelled internal standards before extraction, and recoveries were evaluated using mass-labelled recovery standards, except for PFBS, PFDS, PFDoDA, PFTriDA, and FOSA, for which mass-labelled analogues were unavailable. The 1 ng spiking level was chosen to ensure consistency across compounds, reflecting typical environmental concentrations (sub-ng to ng range) and falling within the quantifiable range (0.01–20 ng/mL) of the LC–MS/MS method. For

PFDS and PFTriDA, surrogate mass-labelled standards (mass-labelled PFOS and PFDoDA, respectively) were used. For most of the compounds, exact matched mass labelled standards were available with the exception of PFDS, PFTriDA that surrogate mass labelled internal standards (mass-labelled PFOS and PFDoDA) were used. Overall, native spiked recoveries were between 58 and 122 % with the relative standard deviation (RSD) at most 14 % of the relative standard deviation (SI Table S5) and the QC fish samples also showed recoveries between 70 and 103 with RSD at most 22 % (SI Table S6). Recoveries of matched mass labelled internal and recovery standards in samples ranged from 50 to 127 %. Internal calibration method with corresponding mass labelled internal standards was used. Initially, two short-chain PFCAs were included in the assessment; the spike recovery test at 1 ng showed good peak shape. However, in the actual sample analysis, interfering peak appeared around the elution time of these compounds. The results of PFBA and PFPeA were not reported. The estimated levels in samples would be less than 500 pg/mL with some uncertainty. Several attempts were made to separate the interfering peaks such as using another column with different combinations of mobile phases and gradient; unresolved peaks remained (SI).

2.3. Food consumption data

The exposure of PFAS in young children, adolescents and adults was calculated based on food consumption data from three national dietary surveys (Riksmaten) conducted by the Swedish Food Agency. Population characteristics of the participants in the Riksmaten surveys are shown in SI Table S8. The Riksmaten Young Children survey was conducted between 2021 and 2023 (Bjermo et al., 2024). A total of 1828 children aged 1.5 and 4 years participated. The consumption data was based on a two-day food diary (one weekday and one weekend day). The Riksmaten Adolescents survey was conducted in 2016–2017 (Moraeus et al., 2018). A total of 3099 adolescents participated from grades 5, 8, and the second year of high school (approximately 12, 15, and 18 years old). The consumption data was based on two retrospective 24-h recalls (one Monday-Thursday and one Friday-Sunday). The Riksmaten Adults survey, included 1797 participants aged 18–80 years and was conducted in 2010–2011 (Becker et al., 2016). The consumption data was based on a four-day food diary. All three surveys also included a questionnaire assessing consumption frequencies of specific fish species. Body weight was primarily measured in child health care and reported by guardians in the Riksmaten Young Children survey, measured by study personnel in the Riksmaten Adolescents survey, and self-reported in the Riksmaten Adults survey. The following number of participants had data on food consumption, questionnaire and weight, and were included in the exposure estimations of the present study: 1.5-year-olds n = 1,008, 4-year-olds n = 686, 12-year-olds n = 1,031, 15-year-olds n = 1,047, 18-year-olds n = 995, women n = 958, and men n = 723.

To be able to combine the consumption data from dietary surveys with the PFAS levels from the market basket study, consumption data from the dietary surveys were grouped according to the food groups in the market basket study. Since the foods in the market basket study were not cooked (with the exception of coffee and tea), while food in the dietary surveys was reported as consumed, the consumption data from the dietary surveys were converted to raw weights. Yield factors can be used to calculate weight gain or weight loss during cooking. The following formula was used to convert to the raw form: raw food (g) = (1/yield factor) * cooked food (g). The following yield factors were used: 0.74 (red meat), 0.76 (poultry) (Østerholt Dalane et al., 2015; Roseland et al., 2017), 0.80 (sausages and black pudding) (Roseland et al., 2017), 0.74 (lean fish), 0.87 (fatty fish) (Østerholt Dalane et al., 2015).

2.4. Exposure estimations

The daily average intake of PFAS (ng/kg bw/day) was calculated using the following equation (WHO, 2020):

$$\text{Daily exposure} = \frac{\sum (\textit{Concentration in food} * \textit{Consumption of food})}{\textit{Body weight (kg)}} * 0.001$$

where PFAS concentration in food was given as ng/kg and consumption of food as g/day.

Four main exposure scenarios were conducted (see Fig. 1): 1) exposure from food using the food groups in the market basket study, 2) exposure from food applying PFAS levels of different fish species based on frequency questionnaire data (SI Table S9) (a), and exposure from food by varying the proportion of wild boar (0, 5, 10, 50 or 100 %) of the total meat consumption (b), and organic eggs (0, 5, 10, 50 or 100 %) of the total egg consumption (c), 3) exposure from food and drinking water at the Swedish maximum limit (4 ng Σ4PFAS/L) (SFA, 2022) and the EU drinking water directive (100 ng PFAS20/L) (EU, 2024), 4) exposure from food and drinking water provided that all participants followed the dietary recommendations for fish (i.e. 2.5 servings/week). Details of the methods for the exposure scenarios are provided in the SI. Exposures of Σ4PFAS and all analysed PFAS (∑PFAS) were estimated for all scenarios. Lower bound (LB) was applied for concentrations below LOQ, as the majority of samples were <LOQ. LB exposure estimates are generally preferred, as they are considered more reliable and reflective of a more realistic assessment of PFAS intake compared to medium or upper bound (EFSA, 2020).

3. Results and discussion

3.1. PFAS levels in food

Detectable levels of PFAS were found in 4 of the 17 food groups in the market basket study (Fig. 2, SI Table S10). These food groups were lean fish, fatty fish, eggs, and coffee/tea. The PFOA concentrations in coffee and tea (0.00045–0.0011 ng/mL) was likely due to PFAS in the drinking water used for brewing, as those drinking water samples also contained PFOA (0.00045 ng/mL in cold water and 0.00085 ng/mL in brewed water). In the specific food samples, PFAS were detected in fish and shellfish, eggs, liver pâté, and in meat from wild boar and reindeer (Fig. 2, SI Table S10). No detectable PFAS were found in foods of plant origin, dairy products, fats/oils, sugar/sweets, or beverages. Overall, the results show that PFAS contamination in Swedish foods is mainly associated with animal-derived products, particularly fish and seafood, while plant-based foods and dairy products contained levels < LOQ. These findings are in line with recent European studies identifying fish and eggs as key contributors to dietary PFAS exposure (EFSA, 2020; Pasecnaja et al., 2022; RIVM, 2023; Van Leeuw et al., 2024). Previous studies have detected PFAS in milk, dairy products, fruits, and vegetables, and EFSA has highlighted fruits as a major contributor to PFAS exposure from food (EFSA, 2020; RIVM, 2023; Van Leeuw et al., 2024; Bonato et al., 2025). In contrast, and in line with our results, recent total diet studies from the US and Australia, reported that most samples of various foods were below detection limits, except for a few food types (i.e. fish (Genualdi et al., 2021; Genualdi et al., 2022; FSANZ, 2021), turkey, protein powder (Genualdi et al., 2021; Genualdi et al., 2022), mammalian offal, prawns, and eggs (FSANZ, 2021)). PFAS levels in food have decreased since the late 1990s, and in previous Swedish market basket studies, PFAS were detected in dairy, meat, and foods of plant origin (SFA, 2024a). This may partly explain discrepancies between studies and highlight the importance of continuous data assessment.

In total, 11 out of 14 analysed PFAS were detected in the food samples (Fig. 2). PFOS was most frequently detected and contributed 15–100 % to the ∑PFAS-levels in all samples, except reindeer (SI Fig. S1). On average, Σ4PFAS contributed 48 % to the ∑PFAS-levels, with a range of 23–100 %. The dominance of PFOS among detected compounds reflects its persistence in aquatic environments and bioaccumulation in the food web.

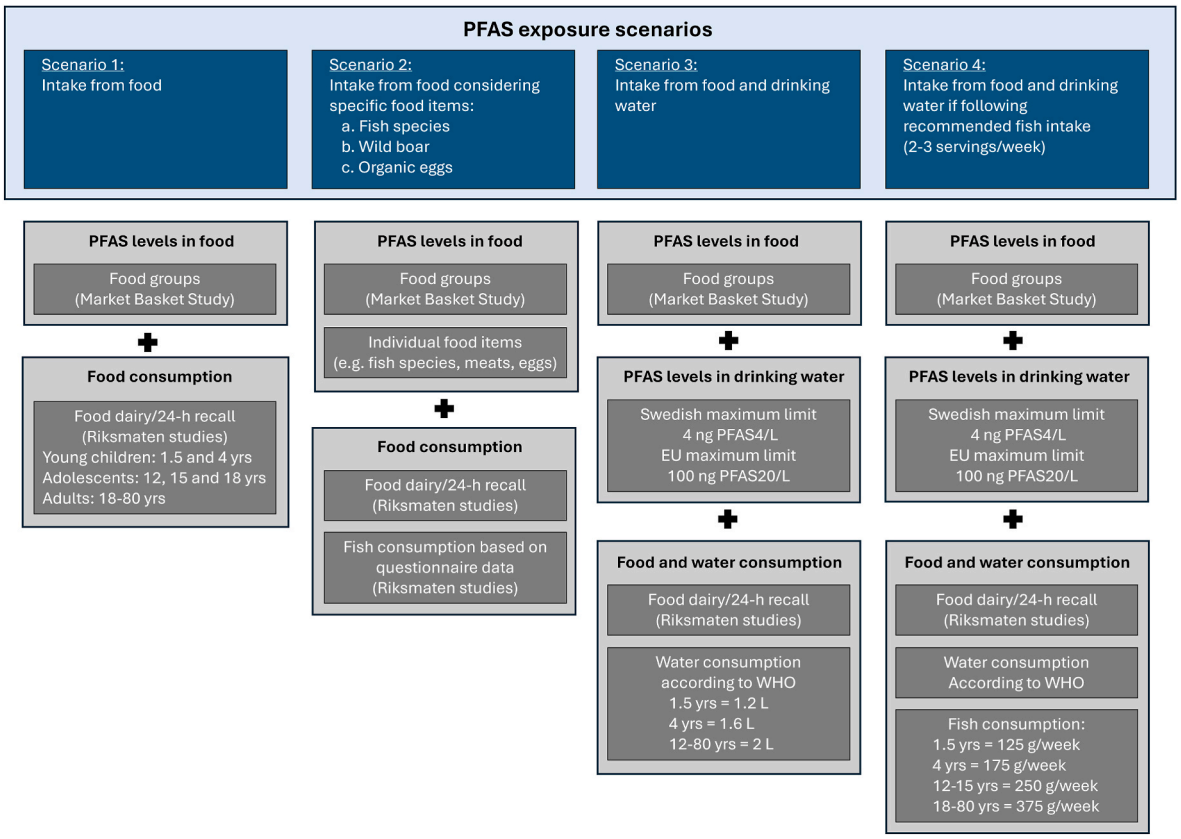

Fig. 1. Exposure scenarios for PFAS from food and drinking water.

Our analyses of individual food items show large variations in PFAS content depending on species and origin (Fig. 2). Among the analysed fish and shellfish samples (n = 50), the highest levels were found in char from Lake Vättern (the second largest lake in Sweden with known contamination), followed by Swedish crayfish and fish from the Baltic Sea (Fig. 2, SI Table S10). In char from Lake Vättern, the average concentration of all detected PFAS was 13 ng/g, with PFOS contributing the most, accounting for 78 % of ∑PFAS (SI Fig. S1). This level was lower compared to char from Norwegian lakes near known contaminated areas (around 20 ng/g for the same ∑PFAS), but higher than measured in a Norwegian lake without known contamination (below 5 ng ∑PFAS/g) (Langberg et al., 2022).

In herring from the Baltic Sea, the mean concentration was higher (1.4 ng ∑PFAS/g) compared to pickled herring from the Northeast Atlantic (0.07 ng ∑PFAS/g). The Σ4PFAS levels in Baltic herring reported in a Finish study (0.72–17 ng/g (Suomi et al., 2024)) was even higher than in the current study (0.4–2 ng Σ4PFAS/g). Similar results as reported here were observed for herring from the North Sea with an average level of 0.24 ng/g for the sum of PFOA, PFNA, PFUnDA, and PFOS (Zafeiraki et al., 2019). In salmon, herring, and pickled herring, PFOS accounted for the majority of ∑PFAS levels, comprising 59–70 % of the measured concentrations (SI Fig. S1).

In lean sea fish such as cod and plaice, as well as tuna, the levels were lower compared to fish caught in smaller lakes and fish from the Baltic Sea (Fig. 2). For white lean sea fish, PFOS contributed to a large proportion of the sum levels (24–53 %), but there were also significant contributions from PFUnDA (12–47 %) and PFNA (0–21 %). PFOS levels were the highest in cod and plaice from the Northern Sea (average levels between 0.9 and 1.1 ng/g for the sum of PFOA, PFNA, PFDA, PFUnDA, PFDoDA, PFTrDA, PFTeDA, PFHxS, and PFOS (Zafeiraki et al., 2019). In canned tuna, PFNA, PFDA, PFUnDA, and PFOS were detected with ∑PFAS of in mean 0.26 ng/g. These results are comparable to findings from canned tuna caught in the Western Pacific Ocean, Eastern Pacific Ocean, and Indian Ocean, where the same PFAS were found in canned tuna (n = 75) in at least one of the samples, and with a mean PFOS concentration of 0.37 ng/g and PFUnDA of 0.28 ng/g (Nobile et al., 2024). In that study, PFBA was also included and had the highest detection rate (89 %), but since this compound was not included in the present study no comparison could be made.

The average levels in farmed char and rainbow trout were significantly lower (0.05–0.1 ng ∑PFAS/g) than those in the wild fish. In these farmed fishes FOSA (63 %) and PFUnDA (56 %) contributed the most (Figs. 2 and 3). The average level in Baltic Sea salmon was about 100 times higher compared to farmed salmon, in terms of ∑PFAS (2.7 vs. 0.03 ng/g). Low levels were also reported in farmed salmon from Norway and Scotland (n = 14) from 2012 to 2018, with PFAS concentrations below the LOQ in most samples (Zafeiraki et al., 2019). The higher PFAS levels observed in wild fish compared to farmed species likely reflect environmental contamination patterns rather than feed sources.

The levels in Swedish crayfish (*Pacifastacus leniusculus*) from the lakes Vänern and Vättern were approximately five times higher (10 PFAS detected; 6.3 ng ∑PFAS/g) compared to crayfish of the same species from Spain (5 PFAS detected; 1.2 ng ∑PFAS/g) (SI Table S10). Lower levels of Σ4PFAS have also been reported in a previous study of crayfish from Swedish lakes (1.4–3 ng/g in Lake Mälaren and 0.7–1 ng/g in Lake Hjälmaren (Karlsson et al., 2024)) compared to 4.5 ng Σ4PFAS/g in crayfish from the lakes Vänern and Vättern in the present study. Σ4PFAS levels contributed 48–76 % of the sum PFAS in Lake Mälaren and Hjälmaren, which also included PFDA, PFUnDA, PFDoDA, and PFTrDA (Karlsson et al., 2024). In shrimp, the contribution to ∑PFAS was relatively evenly distributed among PFUnDA, PFTrDA, and PFOS, and similarly in crab, with additional contributions from FOSA, with sum levels ranging between 1.7 and 2.9 ng/g (SI Table S10).

The various PFAS levels in fish and crayfish from different lakes, such as Lake Vättern and the Baltic Sea, highlight the importance of considering local contamination sources when evaluating dietary exposure.

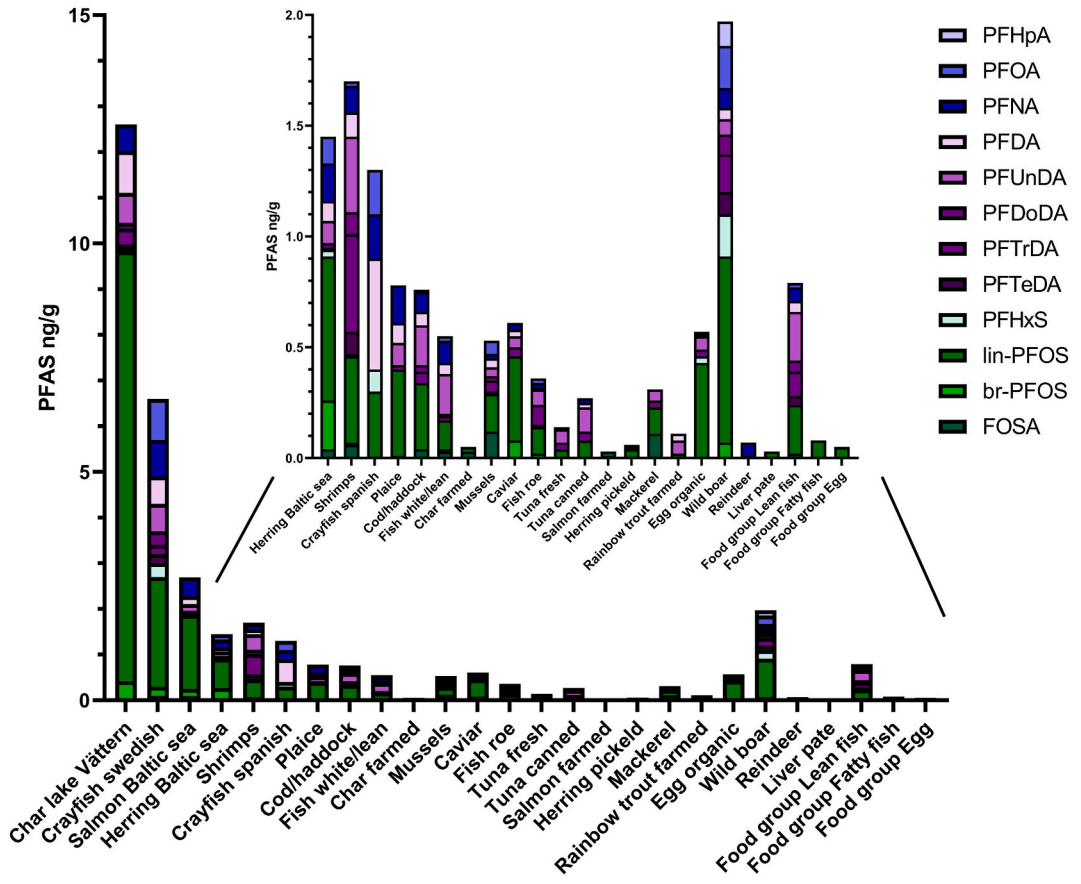

Fig. 2. PFAS levels in food (ng/g) from the Swedish market. Lean fish, fatty fish, and egg were from the market basket study and the other were specific food samples. Food groups with all samples < LOQ (n = 14 from the market basket study) and specific foods with all samples < LOQ (n = 46) were not included in the figure.

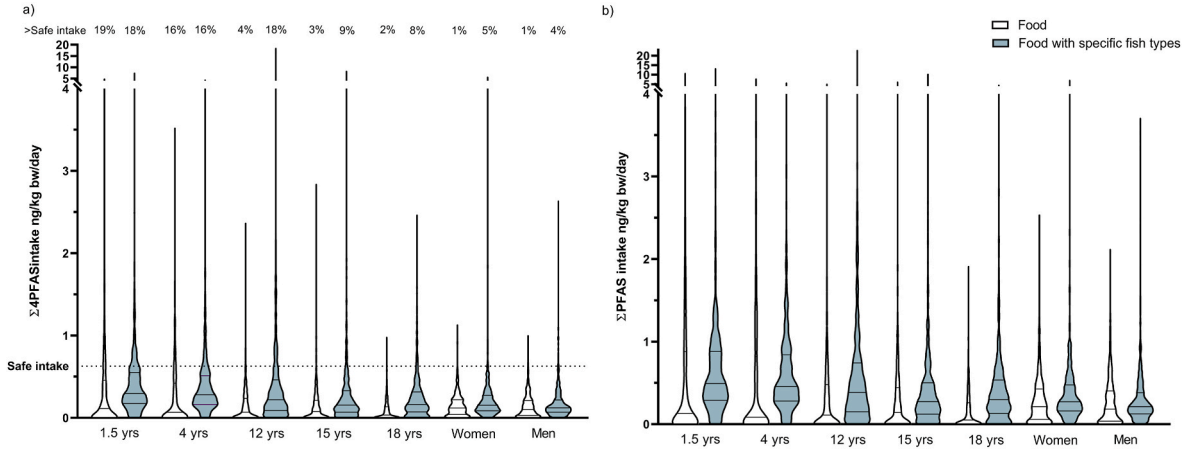

Fig. 3. Estimated daily intake of a) Σ4PFAS (sum of PFOA, PFNA, PFHxS, and PFOS) and b) ∑PFAS, in the Swedish population. Intakes were estimated using Σ4PFAS concentrations from the market basket study and food consumption data (scenario 1, white) or using specific fish type concentrations and fish frequency questionnaire data (scenario 2a, blue). Violin plots showing median and quartiles. Dotted line in a) represents the safe intake of 0.63 ng/kg body weight/day for Σ4PFAS, corresponding to a tolerable weekly intake of 4.4 ng/kg body weight/week established by EFSA. 1.5-year-olds n = 1,008, 4-year-olds n = 686, 12-year-olds n = 1,031, 15-year-olds n = 1,047, 18-year-olds n = 995, women n = 958, and men n = 723.

This exposure should also be included when considering impact on public health and risk management.

Organic eggs contained higher levels of PFAS (mean 0.6 ng ∑PFAS/g) compared to the market basket food group "eggs" including both organic and conventional eggs (0.05 ng/g), and no detectable PFAS were found in the conventional eggs (Fig. 2). Elevated PFAS concentrations have also been found in organic eggs in Denmark, which has been linked to the use of fishmeal in feed (Granby et al., 2024). The mean Σ4PFAS content in organic eggs in that study (1.2 ng/g) was higher compared to the mean levels seen in the present study (0.5 ng/g). Higher levels in organic eggs (mean 0.1 ng Σ4PFAS/g) compared to conventional eggs (all < LOQ) were also measured in a study from Poland (Mikolajczyk et al., 2022).

Almost all of the 31 analysed samples showed levels below the LOQ,

except for wild boar (n = 5), reindeer (n = 2), and one of the two samples of liver pâté. For wild boar and reindeer, the average ∑PFAS concentrations were 2.0 and 0.08 ng/g, respectively, with PFOS and PFNA being the main contributors (Fig. 2 and SI Fig. S1). In liver pâté, only PFOS was detected (0.03 ng/g). Other studies have also reported PFAS levels in wild boar. Similar level as in the present study (1.4 ng Σ4PFAS/g) was reported for average PFOS in Italy (1.4 ng/g) (Arioli et al., 2019). In Germany, levels were reported to be as high as 7.4 ng PFOA/g and 29 ng PFOS/g (Stahl et al., 2012). Again, individuals exclusively consuming organic eggs, and/or eating a lot of wild boars (e.g. hunters) probably have a higher PFAS exposure and may therefore be considered in risk management.

3.2. Exposure assessments

3.2.1. Exposure from food (scenarios 1 and 2)

Exposure estimates of PFAS intake from food show that the median exposure was below EFSA's TWI in all age groups (Fig. 3). When levels in fish from the market basket study (scenario 1) were used in the intake calculations, 16–19 % of young children and 1–4 % of adolescents and adults exceeded the TWI. When using levels in fish from the specific fish samples (scenario 2a), the estimated exposures were higher compared to scenario 1 for most participants. Among those with the highest intakes (i.e. those exceeding TWI), the proportion of young children exceeding the TWI was unchanged (16–18 %), whereas slightly higher proportions were observed among adolescents (8–18 %) and adults (4–5 %). There was a good agreement between the different intake estimates (scenario 1 and 2a) for adults and young children, whereas the agreement was somewhat poorer among adolescents. This is probably due to that adolescents have more difficulties in recalling or identifying the types of fish consumed rather than adolescents eating more PFAS contaminated fish species than young children and adults. Another source of uncertainty is that individuals with higher level of education tend to consume more fish and they are also often overrepresented in dietary surveys, probably leading to a slight overestimation of fish consumption compared to the general population (SFA, 2012; SFA, 2018; SFA, 2024b).

Total exposure estimates for ∑PFAS in scenario 2a showed a 63–84 % higher median intake compared to the intake of Σ4PFAS (Fig. 3). The highest median exposure in scenario 2a was observed in 1.5- and 4-year-olds, at 0.46–0.49 ng ∑PFAS/kg bw/day. For adolescents and adults, the median exposure ranged between 0.27 and 0.39 ng ∑PFAS/kg bw/day and 0.21–0.27 ng ∑PFAS/kg bw/day, respectively. Based on mean exposure, Σ4PFAS accounted for 60–67 % of ∑PFAS, with PFOS contributing to the largest share (SI Fig. S2). Beyond Σ4PFAS, PFUnDA contributed substantially to ∑PFAS (13–18 %), followed by PFTrDA (7–9 %) and PFDA (7–8 %). The results indicate that the Swedish population is exposed to additional PFAS beyond the four for which EFSA has established a TWI, highlighting the urgent need for risk assessments of these substances. In addition, long-chain PFCAs with the molecular formula of CnF2n+1CO2H (where $8 \leq n \leq 20$), their salts and related compounds are also regulated under the Stockholm Convention. These compounds should also be included in future monitoring programmes.

In contrast to the present results, previous dietary intake assessments have reported higher PFAS intakes and that the estimated exposures exceeds the TWI for the general population (EFSA, 2020; BfR, 2021; Pasecnaja et al., 2022; RIVM, 2023). This may be due to higher PFAS levels reported in earlier food studies, as exposure has been shown to decrease over time (Johansson et al., 2014; Sonnenberg et al., 2023; SFA, 2024a; Gyllenhammar et al., 2025), and/or differences in detection limits. In the present study, exposure estimations were made using the LB approach, which was also used by EFSA (2020). This could underestimate exposure from food since most of the food samples in the present study had levels below the LOQ. It is important to develop more sensitive analytical methods to lower detection limits and ensure accurate risk assessment for PFAS in food, a need that has also been highlighted in other studies (Pasecnaja et al., 2022; Eze et al., 2024). The estimated intakes of PFOA and PFOS (SI Table S11) corresponded to median values of approximately 0–2 % and 7–25 %, respectively, of the modeled TWI for these compounds (EFSA, 2020). Such intake levels would result in serum concentrations considerably lower than the calculated safe serum levels for mothers (PFOA: 2.0 ng/mL; PFOS: 4.9 ng/mL (EFSA, 2020)). However, biomonitoring data from the Swedish population indicate that 54 % of first-time mothers sampled during 2018–2022, and 29 % of adolescents sampled during 2016–2017, had serum Σ4PFAS concentrations exceeding EFSA's benchmark concentration of 6.9 ng/mL (Nystrom et al., 2022; Gyllenhammar et al., 2025). These findings highlight that earlier life exposure plays a crucial role and must be considered when predicting serum concentrations from dietary intake estimates.

In the scenario of concentrations in wild boar meat (2b), 5 % of the meat consumed would lead to an exceedance of the TWI for 37–48 % of the young children and 10–16 % for the 12- and 15-year-olds and around 4 % for the 18-year-olds and adult women and men (Fig. 4, SI Table S12). If about half of the meat consumed were at the concentration found in wild boar, almost all (88–97 %) would exceed the TWI (Fig. 4, SI Table S12). The mean level of Σ4PFAS in wild boar in the present study (1.37 ng/g) are close to the EU maximum level for meat of bovine animals, pig and poultry (1.3 ng/g) and meat of sheep (1.6 ng/g) (EU, 2023). The results are therefore comparable for those scenarios as well. The results indicate that there could be parts of the population with high exposure, exceeding the TWI. These are individuals who consume large amounts of wild boar meat or meat produced in a contaminated area. For game meat at the EU maximum level (9.0 ng/g), median exposure exceeded the TWI in all age groups. For the young children, median exposure ranged between 2.2 and 45 ng/kg bw/day, for adolescents, it ranged between 1.1 and 29 ng/kg bw/day, and for adults between 0.9 and 17 ng/kg bw/day (SI Table S12).

Organic eggs have higher Σ4PFAS levels than conventional eggs (SI Table S10). The median exposure was below TWI for all age groups when 100 % of the egg consumption was organic eggs (Fig. 4, SI Table S13). 30–40 % of the young children and about 10 % of the adolescents and adults exceeded TWI in this scenario (2c). The median exposure was also below the TWI for all age groups except for 1.5-year-olds, assuming all egg consumption contained Σ4PFAS at the EU maximum level (1.7 ng/g) (SI Table S13). The results indicate that eggs with higher concentrations of Σ4PFAS could account for up to 50 % of the total egg consumption before a larger proportion of the population would exceed the TWI (SI Table S13). The scenario assuming EU maximum levels is likely overestimated, as measured levels in eggs in the present study were lower. Nevertheless, there could be cases in contaminated areas, such as eggs from home-raised hens with higher concentrations, that may indicate a health concern (Zafeiraki et al., 2016; Lasters et al., 2022; ARS, 2023).

Intake estimations for ∑PFAS in the scenarios with concentrations in organic eggs and wild boar were 1.4–1.8 times higher compared to the intake of Σ4PFAS (SI Table S12 and S13). However, since no health-based guidance value currently exists for ∑PFAS, it is not possible to determine whether this increase in exposure translates to an increased health risk.

3.2.2. Exposure from drinking water and fish recommendations (scenarios 3 and 4)

The consumption of drinking water and fish were shown to be the most significant sources of PFAS exposure. Scenario calculations were performed to examine intake of PFAS from drinking water based on the upcoming Swedish maximum limit for Σ4PFAS in drinking water (4 ng/L), and the intake from fish based on the Swedish Food Agency's dietary recommendations for fish consumption (2–3 servings per week, with a variety of fish species). The exposure was higher when the contribution from drinking water was added to the food intake (scenario 3), causing a 5–7-fold increase in the estimated median exposure for the young children, a 3–5-fold increase for adolescents, and a 2-fold increase for adults

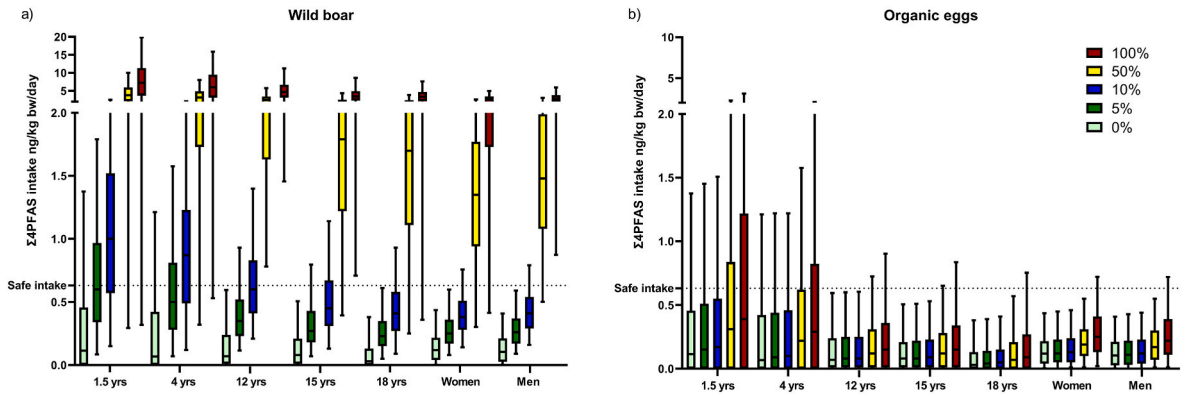

Fig. 4. Estimated scenarios of Σ4PFAS (sum of PFOA, PFNA, PFHxS, and PFOS) intake (ng/kg body weight/day) at a) detected mean level in wild boar (1.4 ng/g) and b) detected mean level in organic eggs (0.49 ng/g). Box plots showing median and the 25th and 75th percentiles, and whiskers show the 5th and 95th percentiles. Dotted line represents the safe intake of 0.63 ng/kg body weight/day for Σ4PFAS, corresponding to a tolerable weekly intake of 4.4 ng/kg body weight/week established by EFSA. 1.5-year-olds n = 1,008, 4-year-olds n = 686, 12-year-olds n = 1,031, 15-year-olds n = 1,047, 18-year-olds n = 995, women n = 958, and men n = 723.

Table 1
Estimated intakes of Σ4PFAS[a] (ng/kg body weight/day) from food, drinking water (DW) and fish consumption at current dietary recommendation of 2–3 servings per week (fish rec). All PFAS levels below LOQ were set to 0 (Lower bound).

Population[b]	Scenario[c]	5th	50th	75th	95th	% > safe intake
1.5 yr	Food	0.00	0.11	0.46	1.36	19
	+DW	0.38	0.55	0.91	1.83	41
	+Fish rec	0.26	0.33	0.40	0.60	4.3
	+DW & fish rec	0.61	0.77	0.86	1.08	93
4 yr	Food	0.00	0.07	0.42	1.19	16
	+DW	0.34	0.47	0.80	1.64	33
	+Fish rec	0.24	0.30	0.34	0.44	0.4
	+DW & fish rec	0.55	0.68	0.75	0.89	76
12 yr	Food	0.00	0.07	0.24	0.59	4.3
	+DW	0.15	0.27	0.43	0.78	11
	+Fish rec	0.11	0.17	0.20	0.25	0.0
	+DW & fish rec	0.24	0.36	0.42	0.50	0.1
15 yr	Food	0.00	0.08	0.21	0.50	3.0
	+DW	0.12	0.22	0.36	0.65	5.9
	+Fish rec	0.09	0.13	0.15	0.19	0.0
	+DW & fish rec	0.19	0.27	0.30	0.36	0.0
18 yr	Food	0.00	0.03	0.13	0.38	1.8
	+DW	0.10	0.16	0.26	0.50	2.7
	+Fish rec	0.11	0.16	0.19	0.23	0.1
	+DW & fish rec	0.20	0.29	0.32	0.38	0.1
Women	Food	0.00	0.12	0.22	0.43	0.7
	+DW	0.11	0.24	0.34	0.56	2.8
	+Fish rec	0.12	0.17	0.19	0.23	0.0
	+DW & fish rec	0.20	0.29	0.32	0.38	0.0
Men	Food	0.00	0.10	0.21	0.41	1.0
	+DW	0.09	0.20	0.31	0.51	2.6
	+Fish rec	0.10	0.14	0.15	0.19	0.0
	+DW & fish rec	0.17	0.24	0.26	0.31	0.0

Safe intake of 0.63 ng/kg body weight/day for Σ4PFAS, corresponding to a tolerable weekly intake of 4.4 ng/kg body weight/week established by EFSA.

[a] Sum of PFOA, PFNA, PFHxS, and PFOS.

[b] 1.5-year-olds n = 1,008, 4-year-olds n = 686, 12-year-olds n = 1,031, 15-year-olds n = 1,047, 18-year-olds n = 995, women n = 958, and men n = 723.

[c] Food corresponds to scenario 1, DW to scenario 3, fish rec and DW & fish rec to scenario 4 in the method section.

(Table 1). When fish consumption was set according to recommendations (2.5 portions per week), PFAS exposure also increased in all groups but to a smaller extent (Table 1). The highest median intake was observed when applying both consumption of drinking water at the maximum limit (4 ng Σ4PFAS/L) and fish at 2.5 servings per week (scenario 4) (Table 1). Almost all 1.5-year-olds (93 %) exceeded TWI in the combined fish recommendations and drinking water scenario, which could be compared to approximately 20 % in the food exposure scenario (scenario 1). The same pattern was observed for 4-year-olds, with a higher percentage exceeding the TWI in the combined scenario (76 %) compared to food intake alone (16 %). For all population groups, the percentage of individuals exceeding the TWI decreased when the recommended fish consumption (2.5 servings per week) was used as a basis, compared to the self-reported fish consumption. The variation in PFAS exposure was also smaller. This indicates that some parts of the Swedish population eat fish more often than 2.5 servings per week (Table 1). If this has any implications on health is however unknown, and assessing benefits with fish consumption vs risk of PFAS exposure from fish was not the scope of this study.

The results indicate that the Σ4PFAS exposure from food and drinking water for most of the Swedish population, except the young children, remain below the TWI, even when drinking water consumption and fish consumption according to the Swedish Food Agency's dietary recommendations are included. Younger children have higher exposure levels, which is expected, as children consume more food relative to their body weight compared to adults.

Other studies have concluded that fish consumption poses a challenge in maintaining tolerable intake levels of PFAS. Langberg et al. (2024) noted that "it seems inevitable that tolerable intake will be exceeded without advice against eating fish at all." Their findings suggest that even limited fish consumption, based on recent tolerable intake or reference dose values in the EU and the US, would lead to exceeding these thresholds. However, the results of the present study indicate a more optimistic outlook, showing that it is possible to consume fish 2–3 times a week, provided that a variety of different fish species are selected. The upcoming risk and benefit assessment of fish consumption by EFSA will play a key role in evaluating the potential negative effects of PFAS from fish.

The Σ4PFAS levels in the present study were all below the EU maximum limits of 2, 8, and 45 ng/g for different fish species and 5 ng/g for shellfish (crustaceans and bivalve mollusks). The highest concentrations were observed in freshwater fish and crayfish; however, the overall consumption of such species is relatively low in the population. Nevertheless, certain individuals with higher consumption patterns may experience exposure levels exceeding the TWI (data not shown). For instance, a single 150 g portion of fish containing Σ4PFAS at the maximum limit of 45 ng/g results in an intake of 96 ng/kg body weight for a person weighing 70 kg. This intake is over 20 times higher than the established safe level of 4.4 ng/kg bw/week, even before considering additional exposure sources. Corresponding calculations for fish and shellfish containing 2, 5, and 8 ng/g results in an intake of 4.3, 11, and

17 ng/kg body weight, respectively.

The estimated intakes of ∑PFAS from food and fish recommendations showed median levels approximately 1.1–2 times higher compared to Σ4PFAS (Table 1 and SI Table S14). In contrast, the drinking water scenario with a concentration of 100 ng/L, corresponding to the EU maximum limit for the sum of 20 PFAS, substantially increased ∑PFAS intake, raising median exposures from 0.05 to 0.13 to 3–11 ng/kg body weight/day. This suggests that drinking water at this level may become a major exposure source, thereby diminishing the relative importance of food intake of ∑PFAS exposure (SI Table S14).

3.3. Strengths and limitations

This study provides a comprehensive investigation of PFAS exposure from food. The food groups included in the Swedish market basket study accounted for more than 90 % of the food consumption in Sweden. Additionally, samples of specific types of fish and shellfish, meat, eggs, fruit, and vegetables were included enabling more detailed intake estimations/scenarios. The food consumption data were nationally representative and covered a broad span of age groups in the population. Another strength is that two exposure assessments were conducted for fish: one using food diary/24-h recall data and another one using questionnaire data with details about fish species. In the second estimate detailed data for different fish species could be considered, both PFAS concentrations and consumption patterns. The study is based on recent concentration data, with food samples purchased in stores during 2022–2023, making the findings highly relevant and generalizable to current exposure. However, many concentrations were below the LOQ and since the lower bound approach was applied, the intake may have been underestimated. The LOQs in the present study were higher than for example, the values recommended in the EU Recommendation 2022/1431 for certain food groups, such as fruits and vegetables. As a result, that may have led to an underestimation PFAS exposure from highly consumed food items with possible low contamination. Additionally, the study does not include the short-chain PFAS compounds, such as PFBA and PFPeA, which may also be present in food (Pasecnaja et al., 2022).

4. Conclusion

Out of the 14 analysed PFAS, 11 were detected in food from the Swedish market. Fish and shellfish had the highest levels and were the main contributors to PFAS exposure from food. The highest exposure was observed in 1.5-year-old children, while adolescents had the lowest exposure. Scenario calculations demonstrated that most of the population, except young children (1.5- and 4-year-olds), could safely consume drinking water at the Swedish maximum limit (4 ng Σ4PFAS/L) and fish according to the recommendation (2–3 servings per week) without exceeding the EFSA TWI. Since PFAS levels in the environment, food, and human exposure are decreasing, updated exposure assessments are crucial. Furthermore, approximately 60 % of sum PFAS exposure from food was attributable to Σ4PFAS, highlighting the need for further risk assessments of other PFAS.

CRediT authorship contribution statement

Irina Gyllenhammar: Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Emelie Lindfeldt:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Leo W.Y. Yeung:** Writing – review & editing, Validation, Resources, Methodology, Investigation. **Emma Halldin Ankarberg:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Helena Bjermo:** Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2025.127488.

Data availability

All data on PFAS in food are in the manuscript. Consumption data can be shared for adults and adolescents but not for the young children due to GDPR.

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