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Cumulative exposure to per- and polyfluoroalkyl substances from eggs and egg products in Europe: application of relative potency factors

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Abstract

Per- and polyfluoroalkyl substances (PFAS) are highly persistent contaminants frequently detected in foods of animal origin, raising concern for human health. Eggs and egg products are recognized by the European Food Safety Authority (EFSA) as one of the major dietary sources of PFAS exposure in Europe. This study applied the relative potency factors (RPFs), based on hepatic toxicity, to estimate cumulative dietary exposure to PFAS from eggs across different population groups. The 95th percentile occurrence data were combined with food consumption patterns to express exposure in perfluorooctanoic acid equivalents, providing a biologically relevant metric. Perfluorooctanesulfonic acid emerged as the dominant contributor to cumulative exposure. Toddlers exhibited the highest estimated weekly intake, reaching 1.63 ng/kg bw per week, while adolescents, adults, and elderly populations showed progressively lower values. These findings highlight children as a particularly vulnerable group due to higher intake per body weight. Consistent with previous studies, commercial eggs generally contained PFAS only at trace levels, whereas home-produced eggs often showed elevated contamination, in some cases exceeding the European Union maximum levels and EFSA's tolerable weekly intake. Overall, this work demonstrates the potential of the RPF approach for mixture-based risk assessment, underscores the need for refined exposure evaluation, and reinforces the importance of continuous monitoring of PFAS in eggs.

Key words: PFAS, risk assessment, RPF, egg products, exposure assessment

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Introduction

Per- and polyfluoroalkyl substances (PFAS) are a large class of synthetic chemicals characterized by high stability and persistence, leading to widespread environmental and food contamination. Human exposure occurs mainly through diet, particularly animal-derived foods, which substantially contribute to internal body burdens (Domingo and Nadal, 2017; EFSA, 2020a; Genualdi *et al*., 2022; Piva *et al*., 2023; Nobile *et al*., 2024; Depau *et al*., 2025; Hossini *et al*., 2025). In 2020, the European Food Safety Authority (EFSA) established a group tolerable weekly intake (TWI) of 4.4 ng/kg body weight (bw) per week for perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA), perfluorooctane sulfonic acid (PFOS), and perfluorohexane sulfonic acid (PFHxS), based on immunotoxicity in children (EFSA, 2020a). These four PFAS were included due to their shared toxicokinetic and toxicological profiles, but they represent only a small subset of the thousands of PFAS identified (OECD, 2021). Some, such as PFOA and PFOS, have also been associated with hepatotoxicity, metabolic effects, developmental toxicity, and, more recently, carcinogenicity (Zahm *et al.*, 2024). Significant data gaps persist for less-studied PFAS, particularly emerging compounds, thereby limiting the robustness of consumer risk assessment. To improve risk assessment and reduce reliance on animal testing, European agencies (European Chemicals Agency and EFSA) promote grouping and read-across strategies (European Chemicals Agency, 2016; EFSA, 2025). In mixture risk assessment, EFSA often applies the relative potency factor (RPF) approach, which expresses the potency of individual substances relative to an index compound, allowing cumulative exposure estimates in equivalent units (EFSA, 2012a; EFSA, 2020b). Bil *et al.* (2021) developed specific RPF for 23 PFAS using liver toxicity as the endpoint, enabling risk characterization in PFOA equivalents (PEQ) (Zeilmaker *et al*., 2018; Bil *et al*., 2021). Recent regulations, including the EU Drinking Water Directive (2020/2184) (European Parliament and Council of the European Union, 2020) and the Directive proposal on the protection of groundwater against pollution and deterioration (COM/2022/540) (European Commission, 2022), have already adopted sum parameters, RPF, and the PEQ concept, highlighting the growing regulatory emphasis on mixture assessment.

EFSA identifies eggs and egg products as one of the major sources of human PFAS dietary exposure (EFSA, 2020a). Several studies have reported the presence of PFAS in eggs, highlighting substantial differences between eggs produced in industrial systems (Gazzotti *et al*., 2021; Chiumiento *et al*., 2023; Nobile *et al*., 2023) and those from backyard hens, with the latter often showing higher

concentrations (Gazzotti *et al*., 2021; Arvaniti *et al*., 2025; Biesterbos and den Braver, 2025). Considering the increasing importance of evaluating as many PFAS as possible in food, as well as their potential implications for consumer health, the present study applies the RPF approach to estimate the cumulative dietary exposure of European consumers to PFAS from eggs and egg-derived products, focusing on hepatic toxicity as the critical endpoint. By integrating occurrence and consumption data and RPF, cumulative exposure is expressed in PEQs, providing a potentially more refined metric for exposure assessment. However, the RPF protocol proposed by Bil *et al*. (2021) has not yet received formal recognition or validation at the European level. As a result, some uncertainty persists, including the possibility of exposure overestimation (Rampazzo *et al*., 2025). Further validation is required before this approach can be routinely applied in regulatory contexts.

Methods and Materials

Per- and polyfluoroalkyl substance occurrence, consumption, and consumer data

Occurrence data on PFAS in eggs and egg products were obtained from the EFSA 2020 scientific opinion on the risk to human health from PFAS in food and reported in Table 1(Annex A) (EFSA, 2020a). The 95th percentile lower bound occurrence values were used, in line with the realistic exposure assessment approach recommended by the EFSA CONTAM Panel (EFSA, 2020a). Consumption data were retrieved from the EFSA Comprehensive European Food Consumption Database. Average European consumption values were calculated as weighted means across Member State surveys for four age groups: toddlers, adolescents, adults, and the elderly, and standard bw for each group applied as recommended by EFSA (Table 2) (EFSA, 2012b).

Perfluorooctanoic acid equivalent exposure evaluation

Occurrence data, combined with mean consumptions and bw, were converted to PEQ using RPFs (Table 3). Exposure was estimated as PEQ using minimum and maximum RPF values.

The estimated weekly intake (EWI) of each PFAS was calculated (1) for each consumer group and expressed in PEQ [Eq. 1]:

$$PEQ - EWI_{PFASi} = \frac{Concentration_i \times RPF_i(min/max) \times Mean\ Consumption}{BW} \times 7 \quad \text{[Eq. 1]}$$

where concentration$_i$ is the concentration of PFAS$_i$ in eggs and egg products (ng/kg); RPF$_i$ is the RPF of PFAS$_i$; mean consumption is the average daily consumption of eggs and egg products (kg/day); BW is the standard bw for the consumer group (kg); and 7 is the conversion from daily to weekly intake.

The cumulative PEQ weekly intake was then calculated [Eq. 2] for each consumer group:

$$Cumulative\ PEQ - EWI = \sum_{j=1}^{n} EWI_{PFASj} \quad \text{[Eq. 2]}$$

Results and Discussion

Table 4 shows the PEQ-EWI across different consumer groups.

Table 1. 95th percentile lower bound of per- and polyfluoroalkyl substances concentration data in eggs and egg products extracted from Annex A of the EFSA 2020 opinion (EFSA 2020a).

Compound	P95 LB (ng/kg)
PFOA	36.0
PFOS	120.0

P95, 95th percentile; LB, lower-bound.

Table 2. European egg and egg products mean consumption and standard body weight used for each consumer group.

Consumer group	bw (kg)	Consumption (g/day)
Toddlers	12	10.1
Adolescents	45	15.9
Adults	70	18.6
Elderly	70	18.3

bw, body weight.

Table 3. Relative potency factors applied based on liver toxicity as a toxicological endpoint. Source: Bil *et al.* (2021).

Compound	RPF	
	min	max
PFBA	0.1	
PFBS	0	
PFDA	4	10
PFDS	2	
PFDoDA	3	
PFHpA	0	1
PFHpS*	0.6	2
PFPeS*	0.001	0.6
PFHxA	0	
PFHxS	0.6	
PFHxDA	0.02	
PFNA	10	
PFOA	1	
PFOS	2	
PFODA	0.02	
PFPeA	0	
PFTeDA	0.3	
PFTrDA*	0.3	3
PFUnDA	4	

*Based on read across (Bil *et al*., 2021). RPF, relative potency factor.

Table 4. Perfluorooctanoic acid equivalent intakes through eggs and egg products.

Consumer group	PEQ (ng/kg bw per week)		
	PFOA	PFOS	Cumulative EWI**
Toddlers	0.21	1.42	1.63
Adolescents	0.09	0.60	0.69
Adults	0.07	0.46	0.53
Elderly	0.06	0.43	0.50

PFOA, perfluorooctanoic acid; PFOS, perfluorooctane sulfonic acid; PEQ, PFOA equivalents; EWI, estimated weekly intake.

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The use of the 95th percentile of occurrence data allows a focused assessment of the contribution of PFOA and PFOS to total PFAS exposure, which is particularly relevant given that the used data on PFAS occurrence in eggs and egg products are not normally distributed. In such distributions, a few highly contaminated samples can disproportionately elevate the mean. In contrast, the 95th percentile provides a more conservative and robust estimate of exposure, minimizing the influence of outliers. Across all age groups, PFOS remains the dominant contributor to exposure. Toddlers exhibit the highest cumulative PEQ-EWI, reaching 1.63 ng/kg bw per week, while adolescents, adults, and the elderly show progressively lower cumulative exposures, corresponding to 0.69, 0.53, and 0.50 ng/kg bw per week, respectively. The application of the RPF approach further strengthens these findings by highlighting the potentially greater contribution of PFOS to hepatic toxicity compared to PFOA, providing a more health-relevant perspective than simple concentration-based estimates.

Overall, this analysis underscores that children may represent a particularly vulnerable population due to their higher intake per bw and the cumulative nature of PFAS. Even at low levels of individual compounds (considering the 4.4 ng/kg bw per week TWI value), their combined effects may still pose a relevant risk, particularly given the recent IARC classifications of PFOA as carcinogenic and PFOS as possibly carcinogenic (Zahm *et al*., 2024). These results are consistent with EFSA's assessment, which identifies eggs and egg products as one of the major sources of human PFAS dietary exposure (EFSA, 2020a). While studies on commercial eggs (Chiumiento *et al*., 2023; Nobile *et al*., 2023) detected only a few long-chain PFAS at trace levels, home-produced eggs (HPE) often show markedly higher contamination. Research in Italy (Gazzotti *et al*., 2021), Belgium (Lasters *et al*., 2022), and Greece (Arvaniti *et al*., 2025) detected PFOS, PFOA, PFHxS, and PFBA at elevated concentrations, in some cases exceeding European maximum levels set for eggs and EFSA TWI. Backyard chickens are more exposed to contaminated soil, foraging, and feed, making HPE a significant contributor to PFAS dietary intake. Dutch risk assessments (Biesterbos and den Braver, 2024) indicate that PFAS exposure from HPE can be 20-80 times higher than from commercial eggs, further underscoring the potential health risks, particularly for children, who are more vulnerable due to higher intake per bw. Moreover, expanding the RPF approach to include additional PFAS and critical endpoints (*e.g*., immunotoxicity) would support the derivation of reference values for data-poor compounds. Integrating predictive methods within the RPF framework could enable more comprehensive and science-based mixture risk assessments, better reflecting real dietary exposure scenarios. Overall, these findings reinforce the importance of continuous monitoring of PFAS in food, the systematic application of mixture-based assessment approaches like RPF, and proactive management strategies aimed at safeguarding vulnerable populations, particularly children, against the potential cumulative and hepatic effects of PFAS in the diet.

Conclusions

In conclusion, this study confirms that eggs and egg products are an important source of dietary PFAS exposure and demonstrates the scientific potential of the RPF approach in dietary PFAS risk assessment. By combining compound-specific potency, occurrence data, and consumption patterns, the RPF framework allows cumulative exposure to be expressed in PEQ, potentially providing a more accurate and health-protective estimate than the traditional concentration-based method. This methodological distinction, however, reflects the proof-of-concept nature of the present study and underscores the need for further validation of the RPF approach before it can be routinely applied in risk assessment. In this context, PFOS may be identified as the dominant contributor to hepatic toxicity, with toddlers as the most vulnerable group due to higher PFAS intake per bw. Beyond its role in exposure estimation, the RPF methodology offers a versatile and robust tool for mixture-based risk assessment and risk management, enabling the prioritization of compounds, identification of high-risk food sources, and the design of targeted mitigation strategies. Its implementation aligns with evolving European regulatory frameworks, which increasingly recognize the need to assess chemical mixtures rather than single substances, reflecting a shift toward more comprehensive and protective approaches in food safety.

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