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Short communication

Human exposure to per- and polyfluoroalkyl substances (PFAS) via the consumption of fish leads to exceedance of safety thresholds

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ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) receive global attention due to their adverse effects on human health and the environment. Fish consumption is a major source of human PFAS exposure. The aim of this work was to address the lack of harmonization within legislations (in the EU and the USA) and highlight the level of PFAS in fish exposed to pollution from diffuse sources in the context of current safety thresholds. A non-exhaustive literature review was carried out to obtain PFAS concentrations in wild fish from the Norwegian mainland, Svalbard, the Netherlands, the USA, as well as sea regions (North Sea, English Channel, Atlantic Ocean), and farmed fish on the Dutch market. Median sum wet weight concentrations of PFOA, PFNA, PFHxS, and PFOS ranged between 0.1 μg kg^{-1} (farmed fish) and 22 μg kg^{-1} (Netherlands eel). Most concentrations fell below the EU environmental quality standard (EQS_{biota}) for PFOS (9.1 μg kg^{-1}) and would not be defined as polluted in the EU. However, using recent tolerable intake or reference dose values in the EU and the USA revealed that even limited fish consumption would lead to exceedance of these thresholds – possibly posing a challenge for risk communication.

1. Introduction

There is a global regulatory, scientific, and citizen focus on per- and polyfluoroalkyl substances (PFAS), due to their negative effects on human health and the environment (Brennan et al., 2021; Tian et al., 2022). A recent study (Cousins et al., 2022) evaluated environmental PFAS levels in the context of planetary boundaries, defined as the "safe operating space for humanity with respect to the functioning of the Earth System" (Rockström et al., 2009; MacLeod et al., 2014). Cousins et al. (2022) concluded that a planetary boundary has been exceeded based on concentrations detected in rainwater, surface water and soil when comparing these to current guideline values. While some of these guideline values are under debate, this illustrates the problematic nature of extensive PFAS pollution in the environment.

In Europe, the political focus on PFAS is spurred on by the European Commission's (EC) Green Deal (EC, 2020a). The Chemicals Strategy for Sustainability Towards a Toxic-Free Environment details the European Union's (EU) new long-term vision for its chemical policy (EC, 2020c). The accompanying Commission Staff Working Document (SWD) for PFAS (EC, 2020b) outlines why existing regulatory tools are not

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Table 1
Previous and present Tolerable daily Intake (TDI) and Reference dose values in the EU and the USA.

	ng kg^{-1}b.w. per day	Applies for	Year	Reference
Previous EFSA TDI which present day EQS are based on	150	PFOS	2008	(EFSA, 2008)
TDI based on the present day EFSA TWI (4.4 ng kg^{-1}b.w. per week)	0.63	Sum of PFOS, PFHxS, PFNA and PFOA	2020	(Schrenk et al., 2020)
Reference dose values used to set advisories in states in the USA	1.8–77	PFOS	–	(Barbo et al., 2023)
The USA EPA reference dose value for PFOS	0.0079	PFOS	2022	(EPA, 2022)

EFSA = European Food Safety Authority.
TWI = Tolerable weekly intake.
PFOS = Perfluorooctane sulfonate.
PFHxS = Perfluorohexane sulfonate.
PFNA = Perfluorononanoic acid.
PFOA = Perfluorooctanoic acid.
EPA = Environmental Protection Agency.

sufficient to address the concerns of PFAS. In addition, the SWD proposes addressing PFAS as a group whilst highlighting the benefit of applying the concept of "essential use" to this group of substances. However, regulation often has to play catch up – policy developments have primarily been retrospective, reacting to a problem rather than proactive, addressing the problem at its source.

The problem of PFAS is not unique and a similar story can be told for other persistent organic pollutants (POPs) such as dichlorodiphenyltrichloroethane (DDT) (Roberts et al., 2016; Arp et al., 2023) and polychlorinated biphenyls (PCBs), which received considerable public attention (e.g., Carson, 1962; Jensen, 1972; Robertson and Hansen, 2001). These chemicals are detected in almost all media and locations sampled (Turusov et al., 2002; Bhaskar et al., 2019). Similarly, PFAS have been found in rainwater, surface water, drinking water, ice cores, groundwater, biota from varying trophic levels, soils, sediments and the air (Rahman et al., 2014; Ahrens et al., 2015; Hale et al., 2017; Rauert et al., 2018; Langberg et al., 2020; Høisæter et al., 2021; Cousins et al., 2022; Hartz et al., 2023). Many PFAS are relatively water soluble and mobile in water, and despite significant environmental transport via sea spray aerosols, the aquatic environment is the ultimate sink for many PFAS (Johansson et al., 2019). As many PFAS bioaccumulate and biomagnify in aquatic food webs, fish are subject to significant PFAS exposure (Ahrens and Bundschuh, 2014; Langberg et al., 2020). In response to information on the problematic properties of many PFAS, five European countries proposed a broad PFAS restriction to The European Chemicals Agency (ECHA) in 2023, which is currently under consultation (ECHA, 2023). However, as PFAS are extremely persistent, their concentrations will not rapidly decrease even after emissions cease. For example, concentrations of perfluorooctane sulfonate (PFOS) were reported to increase in cod (*Gadus morhua*) liver in the Baltic Sea between 1981 and 2013 (Schultes et al., 2019), and concentrations were reported only to be slowly decreasing in cod livers from the Norwegian coast between 2009 and 2021, despite a reduction in PFOS emissions (Schøyen et al., 2022). It has been stated that there is a lack of comprehensive spatial and temporal environmental monitoring in the EU, and that the present state of information only reflects the top of the iceberg (Sonne et al., 2023). It has been postulated that the main uptake route of PFAS to the general population (i.e., for those whose drinking water is not significantly impacted by PFAS) is via food consumption (Vestergren and Cousins, 2013), especially consumption of fish and other seafood (Schrenk et al., 2020). It has been reported that PFAS intake via fish consumption may pose a risk of exceedance of safety limits for certain groups of the population (Barbo et al., 2023; Schepens et al., 2023). PFAS have been detected in fish from Asia (Lam et al., 2014; Thi et al., 2022), Africa (Abafe et al., 2021), North America (Lescord et al., 2015; Goodrow et al., 2020), South America (Miranda et al., 2021), Arctic (Muir et al., 2019), Antarctica (Gao et al., 2020), Europe (Åkerblom et al., 2017; Valsecchi et al., 2021), and Australia/Oceania (Taylor et al., 2018), confirming ubiquitous contamination.

In this perspective we reflect upon PFAS concentrations in fish polluted by diffuse sources (fish that are not directly affected by a nearby PFAS pollution point source). Previous examples have shown that concentrations of PFAS in the environment are challenging for society: in the Netherlands, building work was temporarily halted in 2019 as PFAS concentrations in soil exceeded the thresholds set for moving soil (0.9 μg kg^{-1} for PFOS and 0.8 μg kg^{-1} for perfluorooctanoic acid (PFOA)) (Wintersen et al., 2019, 2020). PFAS concentrations in rainwater are above drinking water thresholds, calling into question the use of rainwater as a source of drinking water (Cousins et al., 2022). Adding to this, a recent report by the Dutch National Institute for Public Health and the Environment (RIVM; Bilthoven, The Netherlands) concluded that PFAS levels in Dutch surface water must decline to avoid the contribution of drinking water exceeding 20 % of the tolerable daily intake (TDI; Monique et al., 2021). In Denmark, it has been reported that for the 95th percentile of the population PFAS exposure via the consumption of eggs alone exceeds the of the tolerable weekly intake set by The European Food Safety Authority (EFSA) (DTU National Food Institute, 2023). Herein, fish concentrations are compared to current EU environmental quality standards (EQS), as well as current thresholds for tolerable human intake of PFAS in the EU and the USA. We consider whether fish consumption constitutes a risk for exceedance of these thresholds, and challenges related to risk communication.

2. Thresholds and guideline values in the EU and the USA

Thresholds and guideline values vary between areas and have changed over time as detailed for the EU and the USA in the following. Previous and present safety thresholds in the EU and the USA are summarized in Table 1.

As pointed out by Cousins et al. (2022), concentrations of PFOS in surface freshwaters and rainwater exceed the EQS in the EU Water Framework Directive (WFD). The EQS is based on the most critical of the specific quality standards (QS), i.e., the strictest of the QS set to protect top predators ($QS_{biota,\ secpois}$) and the QS for protecting human health ($QS_{biota\ h,h}$). For PFOS, the most critical QS was $QS_{biota\ h,h}$ (EC, 2011b). As shown below, the $QS_{biota\ h,h}$ (that the EQS for water is based on) does not (yet) include new toxicity information.

In 2008, the Scientific Panel on Contaminants in the Food Chain (CONTAM) defined the lowest no-observed-adverse-effect level (NOAEL) for PFOS of 0.03 mg kg^{-1} body weight (b.w.) per day (EFSA, 2008). This value was based on changes in serum levels of high-density lipoprotein cholesterol and thyroid hormones in a single study with Cynomolgus monkeys (*Macaca fasicularis*) (Seacat et al., 2002). By applying an uncertainty factor (UF) of 200 to the NOAEL, a TDI of 150 ng kg^{-1}b.w. per day was established (EFSA, 2008). The TDI was used, together with a factor for the relative source contribution from fish consumption, to calculate $QS_{biota\ h,h}$ for PFOS in biota of 9.1 μg kg^{-1} wet weight (w.w.) (EC, 2011b, 2011a), as shown in Eq. (1).

$$QS_{biota,hh} = \frac{0.1 \times TDI \times b.w.}{Fish_{intake}} \quad (1)$$

The factor 0.1 is from the assumption that PFOS intake via fish consumption contributes 10 % of total PFOS intake; b.w. is body weight (70 kg); and $Fish_{intake}$ is the average fish consumption per day (0.115 kg day^{-1}).

As $QS_{biota\ h,h}$ (9.1 μg kg^{-1}) was the strictest QS, it was used as the EQS for biota (defined as fish) in the WFD. The QS for PFOS in freshwater and saltwater, $QS_{freshwater}$ (0.65 ng/L) and $QS_{saltwater}$ (0.13 ng/L) respectively, were then derived based on $QS_{biota\ h,h}$ (using bioconcentration

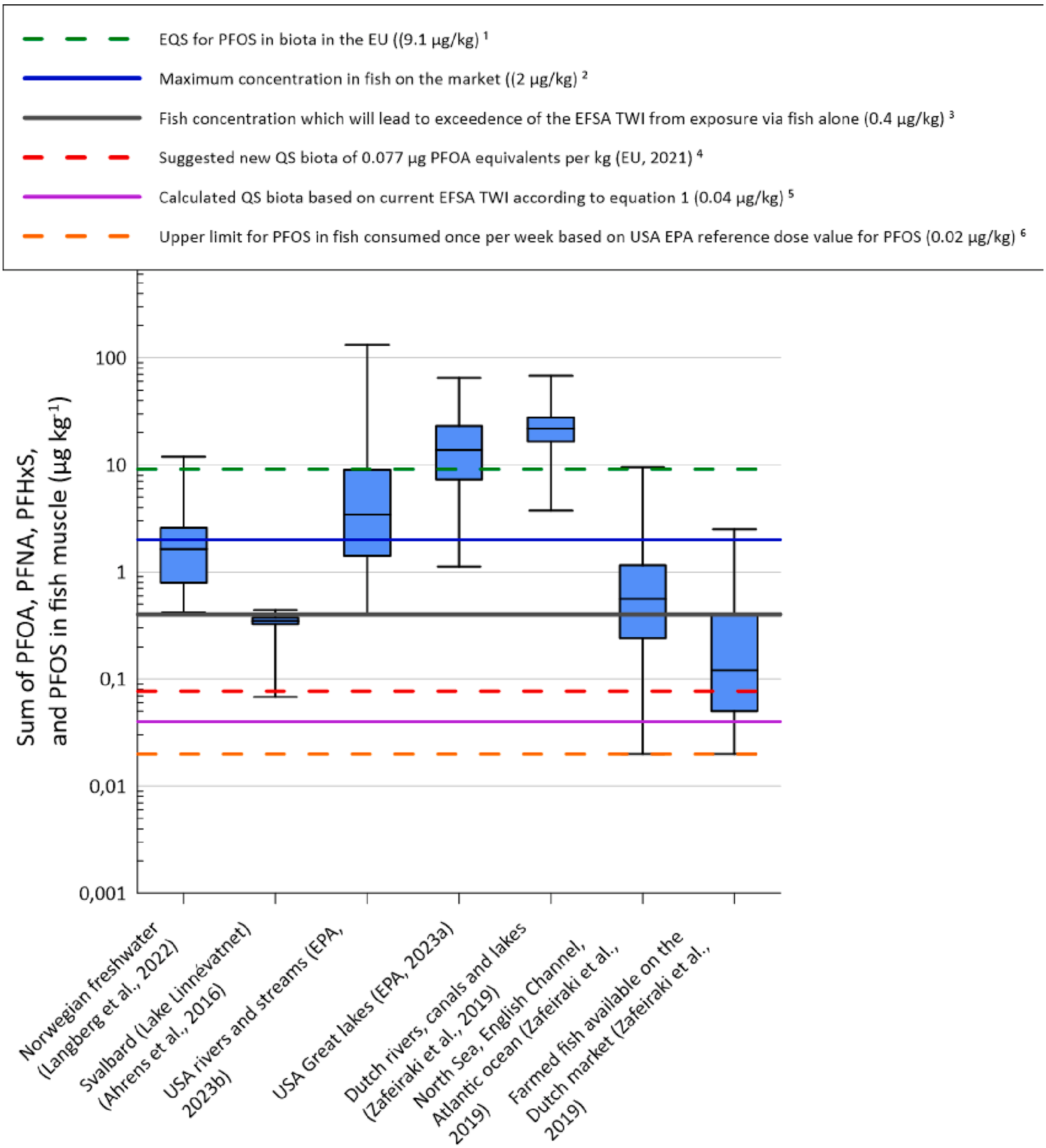

Fig. 1. Sum concentrations of four PFAS (perfluorooctanoic acid [PFOA], perfluorononanoic acid [PFNA], perfluorooctane sulfonate [PFOS], and perfluorohexane sulfonate [PFHxS]) in fish muscle. Boxes indicate the 25th and 75th percentiles, respectively. Centre lines show the medians, and the whiskers indicate the ranges (i.e., max and min). Concentrations below the LOQ were treated as LOQ/2. Selected limit values and thresholds are indicated with lines. Dashed lines show thresholds for other parameters than the sum of the four PFAS (PFOS only or sum of PFOA equivalents). Note: [1] Environmental Quality Standard (EQS) for PFOS in the EU (Directive, 2013/39/EU, 2013). The threshold apply for PFOS only. [2] Maximum concentrations allowed in fish on the European market (EC, 2022). Maximum concentrations were set higher for some specific fish species when not intended for the production of food for infants and young children (EC, 2022). [3] Fish concentration which will lead to exceedance of the Tolerable Weekly Intake (TWI) from the European Food Safety Authority (EFSA) by exposure via fish alone. [4] Suggested new Quality Standard (QS) for biota in the EU (EU, 2021). The red dashed line indicates the threshold for the sum of 24 PFAS expressed as PFOA equivalents. [5] Calculated QS biota based on the current TWI from EFSA according to Eq. (1). [6] The upper limit of the range of maximum levels of PFOS in fish consumed in one meal per week calculated based on the USA Environmental Protection Agency's (EPA) reference dose value and the most widely adopted approaches used by states in the Great Lakes Consortium for Fish Consumption Advisories (Barbo et al., 2023). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Concentrations of linear perfluorooctane sulfonate (L-PFOS) as well as the sum of perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA), perfluorohexane sulfonate (PFHxS), and PFOS in fish muscle from the Norwegian mainland, Svalbard, the Netherlands and the USA, as well as wild fish from the sea (North Sea, English Channel, and Atlantic Ocean), and farmed fish available on the Dutch market. Median, mean, maximum and minimum concentrations (μg kg^{-1} w.w.) as well as the percentage of concentrations below the limit of quantification (LOQ) are listed for each dataset. Concentrations below the LOQ were treated as LOQ/2.

Data source	Number of species	L-PFOS (μg kg^{-1} w.w.)	Sum PFOA, PFNA, PFHxS, and PFOS (μg kg^{-1} w.w.)
Freshwater fish (Norwegian freshwater bodies) (n = 315) (Langberg et al., 2022)[1]	4 different species	Median: 0.7 Mean: 1.1 Max: 8.9 Min: <LOQ Below LOQ: 9.8 %	Median: 1.6 Mean: 2.0 Max: 12 Min: <LOQ Below LOQ: 9.8 %
Freshwater fish (Lake Linnévatnet on Svalbard, Norway) (n = 6) (Ahrens et al., 2016)	1 species (Arctic char (*Salvelinus alpinus*))	Median: 0.2 Mean: 0.2 Max: 0.3 Min: 0.02 Below LOQ: 0 %	Median: 0.3 Mean: 0.3 Max: 0.4 Min: 0.1 Below LOQ: 0 %
Freshwater fish (Rivers and streams in the USA (n = 290) (EPA, 2023b) [2]	37 different species	Median: 3.2 Mean: 7.7 Max: 131 Min: <LOQ Below LOQ: 8.6 %	Median: 3.4 Mean: 8.0 Max: 131 Min: <LOQ Below LOQ: 7.2 %
Freshwater fish (USA Great Lakes) (n = 152) (EPA, 2023a) [2]	17 different species	Median: 12.4 Mean: 16.9 Max: 64.4 Min: 0.5 Below LOQ: 0 %	Median: 13.8 Mean: 18.1 Max: 65.2 Min: 0.7 Below LOQ: 0 %
Freshwater fish (Dutch Rivers, canals, and lakes) (n = 86) (Zafeiraki et al., 2019)	1 species (European eel (*Anguilla anguilla*))	Median: 20 Mean: 22 Max: 67 Min: 3.3 Below LOQ: 0 %	Median: 22 Mean: 23 Max: 68 Min: 3.8 Below LOQ: 0 %
Marine fish (North Sea, English Channel, Atlantic ocean) (n = 77) (Zafeiraki et al., 2019)	10 different species	Median: 0.3 Mean: 0.8 Max: 9.4 Min: <LOQ Below LOQ: 38 %	Median: 0.6 Mean: 1.0 Max: 9.4 Min: <LOQ Below LOQ: 27 %
Farmed fish (on the Dutch market) (n = 52) (Zafeiraki et al., 2019)	7 different species	Median: 0.03 Mean: 0.2 Max: 2.0 Min: <LOQ Below LOQ: 69 %	Median: 0.1 Mean: 0.4 Max: 2.5 Min: <LOQ Below LOQ: 58 %

[1] Only data from water bodies reported to not be directly influenced by a PFAS point source were included. [2] Compared to Barbo et al. (2023), the present study reviewed the same dataset for the USA Great Lakes (2015) and a newer dataset from the same USA monitoring program for rivers and streams (2018–2019).

[BCF] and biomagnification [BMF] factors). However, based on decreased immune responses observed in children, in 2020 EFSA set a tolerable weekly intake (TWI) threshold for the sum of PFOA, PFOS, perfluorononanoic acid (PFNA), and perfluorohexane sulfonate (PFHxS) of 4.4 ng kg^{-1}b.w., which corresponds to a TDI of 0.63 ng kg^{-1}b.w. per day (Schrenk et al., 2020). Thus, the 2020 TDI for the $\sum$ PFOA, PFOS, PFNA, and PFHxS is approximately 1/238 of the TDI from 2008 for PFOS (150 ng kg^{-1}b.w. per day) for which present-day EQS are based on.

In 2022, the EC published an amendment to Regulation No 1881/2006 setting maximum levels of PFAS in foodstuffs on the market (EC, 2022). A general maximum level for the sum of PFOS, PFOA, PFNA and PFHxS in fish muscle was set at 2 μg kg^{-1} w.w. (blue line in Fig. 1), while the maximum levels for some fish species were set higher (8 and 45 μg kg^{-1} w.w. respectively, depending on species) when not intended for the production of food for infants and young children (EC, 2022). Assuming a body weight of 70 kg (as in Eq. (1)), a person consuming fish containing the general maximum level of 2.0 μg kg^{-1} w.w. would exceed the EFSA TWI when they consume more than 154 g of fish per week, without other sources of PFAS exposure. Consumption of 154 g of fish per week is low compared to the estimated average fish consumption used in Eq. (1) (115 g per day, or 805 g per week). It is important to notice that this number (154 g per week) does not take into account PFAS intake from other sources than fish exposure (which in Eq. (1) was estimated to contribute to 90 % of the PFAS intake). Consuming even a few grams of fish containing PFAS concentrations corresponding to the new maximum levels for specific fish species of 8 and 45 μg kg^{-1} w.w. (i.e., 39 and 7 g of fish per week, respectively) will lead to exceedance of the present-day TWI, without any other sources of PFAS exposure. Thus, the new maximum levels of PFAS in foodstuff are high considering the new EFSA TWI (4.4 ng kg^{-1}b.w.) and PFAS intake from other sources than fish consumption. Denmark, Germany, the Netherlands, and the Czech Republic have submitted a note to the General Secretariat of the European Council recommending regular reviews, a lowering of existing maximum levels for PFAS in foodstuffs, and setting new maximum levels in additional foodstuffs based on occurrence data in food (General Secretariat of the Council of the European Union, 2023).

Fish advisories in the USA have been under scrutiny and are not coherent between states (Barbo et al., 2023). Reference dose values (similar to the tolerable intake value in the EU) for PFOS, used to set the advisories in the different states, varied between 1.8 and 77 ng kg^{-1} b.w. per day (Massachusetts and Alabama, respectively) (Barbo et al., 2023). In 2022, the USA Environmental Protection Agency (EPA) published a reference dose value for PFOS of 7.9×10^{-3} ng kg^{-1} b.w. per day (EPA, 2022). Based on the EPA's reference dose value and the most widely adopted approaches used by states in the Great Lakes Consortium for Fish Consumption Advisories, Barbo et al. (2023) calculated a maximum level of 0.008–0.02 μg kg^{-1} for PFOS in fish consumed in one meal per week (the upper limit of this range, 0.02 μg kg^{-1} is indicated as an orange dashed line in Fig. 1).

In conclusion, there is a lack of harmonization within legislations (in the context of tolerable intake) in the EU and the USA. As the consumption of fish and other seafood is reported to be among the most important sources of PFAS exposure to humans, it is relevant to compare concentrations of PFAS in muscle of fish to present-day limit values and tolerable intake estimates. Fish concentrations, relative source contribution from fish consumption, as well as the threshold value for human health used in this comparison will have implications on the amount of fish that can be eaten without exceeding threshold values.

3. Concentrations of PFAS in fish exposed to pollution from diffuse sources

The aim of this study was not to perform a comprehensive review of PFAS concentrations in fish, but to highlight the level of PFAS in fish exposed to pollution from diffuse sources in the context of current safety thresholds. The dataset below presents a non-exhaustive summary of concentrations of PFAS in wild freshwater fish from the countries of the authors' home institutes in Europe (Norwegian mainland, Svalbard, Netherlands) and the USA, as well as wild fish from the sea (North Sea, English Channel, and Atlantic Ocean), and farmed fish available on the Dutch market. Fish concentrations from areas known to be substantially polluted by a particular PFAS point source were excluded from the dataset. Table 2 shows the concentrations of PFOS as well as the sum of PFOA, PFNA, PFHxS, and PFOS (the parameters most relevant for comparison to the thresholds and guideline values listed above) in fish muscle from these areas. Concentrations are shown for the linear isomer and are compared to relevant thresholds in Fig. 1.

4. Comparison of fish data to EQS, and safety thresholds for tolerable intake

There are relatively large differences in PFAS concentrations between the datasets in Table 2. Differences in regional PFAS loads, dilution potential in different water bodies (i.e., freshwater lakes compared to the sea), uncertainties of the analytical methods applied, as well as species are likely some of the explanations for this. Based on the data shown here, it seems that marine fish as well as farmed fish have lower PFAS loads compared to fish from most freshwater sources. A previous study investigating purchased fish in the Netherlands, showed that PFAS concentrations in wild-caught cod and tuna were higher than farmed salmon and pangasius (Schepens et al., 2023).

Except for Dutch eel and fish from the USA Great Lakes, PFAS concentrations in the above reviewed fish are mostly below the present-day EU EQS_{biota} of 9.1 μg kg^{-1} w.w. (dashed green line in Fig. 1) and would therefore not be defined as polluted in the EU. However, given the recent EFSA data (Schrenk et al., 2020), the EQS of 9.1 ug kg^{-1} w.w is now under scrutiny. An assessment by the Norwegian Institute of Public Health (NIPH, 2020) showed that the current EFSA TWI (4.4 ng kg^{-1}b.w. per week) is exceeded for Norwegian children even when PFAS from fish and drinking water consumption are excluded. The data also show that the TWI is exceeded for women when only fish consumption (i.e., without drinking water consumption) is included in the assessment (NIPH, 2020). To ensure that the TWI for adult men and women is not exceeded, the maximum permissible concentrations of PFAS in fish were 0.27 and 0.23 μg kg^{-1}, respectively (NIPH, 2020). Similarly, RIVM calculated the PFAS exposure for the Dutch population and concluded that it exceeds the EFSA TWI, and that fish is an important source of PFAS (Schepens et al., 2023). EFSA has reported that exposure of European children, as well as major parts of the adult population exceeds the present-day TWI (Schrenk et al., 2020). Studies published in the scientific literature have also concluded that human PFAS exposure exceeds health-based guidance values (see e.g., Bil et al. (2023), Uhl et al. (2023) and Brambilla (2024)). Further, a simple calculation shows that a 70 kg person consuming 115 g of fish per day (the values used in eq (1)) would exceed the current EFSA TWI (4.4 ng kg^{-1}b.w. per week) from fish alone if the PFAS concentration in fish muscle exceeded 0.4 μg kg^{-1} w.w. (black line in Fig. 1). However, as the above examples illustrate, fish is not the only source of human exposure to PFAS. If an EQS_{biota} was calculated using the current EFSA TWI according to eq (1), (i.e., assuming 10 % of the TWI could come from fish), the concentration would be 0.04 μg kg^{-1} w.w. (purple line in Fig. 1). As can be seen from Fig. 1, this value is lower than concentrations in most fish. It is also important to note that the value of 0.04 μg kg^{-1} w.w. is lower than most detection limits achieved in routine analysis. For example, the required quantification limit for PFOS, PFOA, PFNA and PFHxS is 0.10 μg kg^{-1} according to European Union Reference Laboratory for halogenated POPs in Feed and Food (2022).

Regardless of whether one concludes that the EQS_{biota} should or should not be calculated using Eq. (1) with the lower EFSA TWI, the current limit values and tolerable intake estimates are not harmonized. In fact, a new $QS_{biota\ h,h}$ of 0.077 μg PFOA-equivalents per kg biota (red dashed line in Fig. 1) has been suggested (EU, 2021). This value is based on the current EFSA TWI (4.4 ng kg^{-1}b.w. per week) and the EC's updated method for calculating $QS_{biota,\ hh}$, i.e., using data on fish intake in the general population in Europe and assuming that 20 % of the total PFAS intake comes from fishery products (EC, 2018; EU, 2021). Comparing the fish data reviewed herein to the maximum level of 0.008–0.02 μg kg^{-1} for PFOS in fish consumed in one meal per week (the level calculated by Barbo et al. (2023), as detailed in section *Thresholds and guideline values in the EU and the USA*) shows that most fish exceed this level. Barbo et al. (2023) concluded that an individual's consumption of freshwater fish is potentially a significant source of exposure to PFAS. That conclusion is in line with indications of the comparisons performed in the present study. These considerations can have serious consequences for the global seafood industry. Overall, the concentrations of PFAS in fish reviewed here are high compared to the present-day EFSA TWI and US EPA reference dose value. Limit values calculated based on present-day EFSA TWI and EPA reference dose value are below the detection limit in most studies (as stated above), which is problematic. Given the current technology, any detection may have to be defined as an exceedance if these values are implemented.

5. How to best communicate risk

It is, in our opinion, important to communicate the potential risk of consuming fish that are contaminated with PFAS from diffuse sources as well as from point sources. However, it is vital to balance and correctly communicate these risks to enable the public to make informed decisions. Fish is an important source of proteins as well as vital micronutrients for human populations around the world (Golden et al., 2016). One possible approach is to provide balanced general advice on the amount (i.e., grams) of fish that can be consumed per week without exceeding thresholds. Such advise should take into account the total amount of PFAS exposure the general population is exposed to, including exposure from sources such as food packaging (Trier et al., 2011; Xu et al., 2013) as well as potential effects of cooking methods (Taylor et al., 2019; Hu et al., 2020). In addition, specific and tailored risk communication could be used for regional areas, freshwater versus seawater fish, or wild caught versus farmed fish. Tailored advice for some locations polluted by nearby PFAS sources are already given. In

2020, the Norwegian public was advised against consuming fish from waters that are polluted by PFAS from a factory producing paper products (Lake Tyrifjorden) and fish from freshwater bodies near airports which are polluted due to the use of aqueous film forming foam (AFFF) for firefighting activities (Mattilsynet, 2024b, 2023). In The Netherlands, RIVM advises reducing consumption to a minimum for fish, oysters, and clams from River Western Scheldt, which is polluted by emissions from the 3M company in Antwerp, Belgium (RIVM, 2022). In the USA, 14 out of 50 states have issued fish consumption advisories for specific water bodies or fish (Barbo et al., 2023). This approach could be extended to region-specific recommended amounts of consumption of fish only exposed to pollution from diffuse sources. In addition, PFAS exposure via consumption of locally caught freshwater fish can disproportionally affect different groups in the population (Barbo et al., 2023). Specific advice for wild freshwater fish is already given in Norway due to the mercury content, where the advice is to not eat large wild caught freshwater fish (Mattilsynet, 2024a). Furthermore, pregnant or breastfeeding women, as well as small children, are advised against eating wild caught freshwater fish at all (Mattilsynet, 2024a). Based on possible pollution with dioxins, PCBs, and PFAS, the Netherlands Nutrition Center advises against the consumption of specific species of freshwater fish from Dutch surface waters (Voedingscentrum, no date).

One obstacle with such an approach is population groups that exceed safety thresholds even without including fish consumption, such as Norwegian children (NIPH, 2020). The large number of PFAS that are, or have been, on the global market (Wang et al., 2017) represent an unknown risk, as present thresholds only account for a few PFAS. Another challenge is the lack of structured concentration data needed for informed decision making. A structured overview of data on PFAS concentrations in fish would support tailored advice specific for regions or population groups. Further, the way in which the above-mentioned existing advisories have affected the dietary choices of the general public is, to the best of our knowledge, unknown.

6. Conclusion

We conclude that the global contamination of fish with PFAS may be of concern in the context of human fish consumption. This adds to the growing body of evidence that global PFAS contamination poses a risk for the world's population, and not only highly exposed individuals. The question remains as to how to tackle this problem.

Several legislations are currently being revised and the hope is a more harmonized policy framework where guideline values are streamlined. Several approaches and strategies are currently being developed and adopted to reduce emissions, such as source control and safe and sustainable by design strategies (Hale et al., 2022). However, it seems inevitable that tolerable intake will be exceeded without advice against eating fish at all. Fortunately, scientists have the tools to close the data gap related to concentrations of known PFAS in fish exposed to diffuse pollution. Mapping and compiling searchable databases of PFAS pollution in fish around the world would help supply data for informed decision making. A similar effort was performed by the Forever Pollution Project, which recently published an overview of more than 17 000 sites where PFAS contamination has been detected in Europe (Le Monde, 2023). With more data, risk communication becomes more informed, and the public can be provided with the correct information to make informed decisions.

CRediT authorship contribution statement

Håkon Austad Langberg: Writing – review & editing, Writing – original draft, Visualization, Investigation, Data curation, Conceptualization. **Gijsbert D. Breedveld:** Writing – review & editing, Supervision, Project administration. **Roland Kallenborn:** Writing – review & editing. **Aasim M. Ali:** Writing – review & editing. **Sarah Choyke:** Writing – review & editing. **Carrie A. McDonough:** Writing – review & editing. **Christopher P. Higgins:** Writing – review & editing. **Bjørn M. Jenssen:** Writing – review & editing. **Morten Jartun:** Writing – review & editing. **Ian Allan:** Writing – review & editing. **Timo Hamers:** Writing – review & editing. **Sarah E. Hale:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

Christopher P. Higgins is involved in various PFAS litigation activities. The other 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.

Data availability

Data will be made available on request.

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