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Review article

Human exposure to per- and polyfluoroalkyl substances (PFAS) through drinking water: A review of the recent scientific literature

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ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) are a group of water-soluble chemical compounds with an important number of applications, which have been widely used during the last 60 years. Two of them, perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA), are the most known and well investigated. As for many other organic substances that are of environmental concern, the diet is the main route of human exposure to PFAS. However, in certain cases drinking water may also mean a significant contribution to human exposure, and to a lesser extent, dust and air (indoor exposure). In recent years, the environmental persistence of PFAS, their biomagnification in food webs, as well as their potential accumulation and toxicity, have generated a notable interest, which has been evidenced by the considerable number of publications in this regard. Recently, we carried out a wide revision on the levels of PFAS in food and human dietary intake. In the current review, we have summarized the recent information (last 10 years) published in the scientific literature (Scopus and PubMed) on the concentrations of PFAS in drinking water and the human health risks derived from the regular water consumption, when available. A large amount of data belongs to PFOS and PFOA and corresponds to studies mainly conducted in countries of the European Union, USA and China, although no information is available for most countries over the world. According to the toxicological information about PFAS that is so far available, the current health risks for the regular consumers of municipal/tap water do not seem to be of concern according to the levels considered as acceptable for various regulatory institutions.

1. Introduction

Perfluorinated compounds (PFC) are a group of chemicals that have been manufactured for over 60 years. They are particularly characterized by their surface manufacture properties, which make that these compounds have a great number of applications. Among the PFAS, stand out the per- and polyfluoroalkyl substances (PFAS), which, among many other compounds, include perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS), the two most extensively produced and studied PFAS (Fàbrega et al., 2014). They have been used in a great variety of industries over the world (US EPA, 2019). However, PFOS and related compounds have been also designated as target chemicals for regulation by the Stockholm Convention on Persistent Organic Pollutants (POPs), an international environmental treaty, signed in 2001, and effective from May 2004, aimed at eliminating -or restricting-the production and use of POPs.

The general population may be exposed to PFAS through the diet, including drinking water, as well as indoor environments polluted with PFAS (Nadal and Domingo, 2014; Sjogren et al., 2016; Mastrantonio et al., 2018; Winkens et al., 2017, 2018; Andersson et al., 2019; Park et al., 2019; Rovira et al., 2019; Sunderland et al., 2019; Zhou et al., 2019). Actually, the intake of contaminated foods, or the migration of PFAS from food packaging or cookware, are key sources of human exposure to PFAS (Jogsten et al., 2009; Domingo, 2011, 2012; Domingo et al., 2012; Ericson Jogsten et al., 2012). In an exhaustive study performed in Tarragona County (Catalonia, Spain), we found that the

Abbreviations: PFC, Perfluorinated compounds; PFAS, per- and polyfluoroalkyl substances; PFOA, perfluorooctanoic acid; PFOS, perfluorooctane sulfonate; PFBA, perfluorobutanoic acid; PFBS, perfluorobutane sulfonate; PFHxS, perfluorohexane sulfonate; PFHxA, perfluorohexanoic acid; PFPeA, perfluoropentanoic acid; PFHpA, perfluoroheptanoic acid; PFNA, perfluorononanoic acid; PFDA, perfluorodecanoic acid; PFPA, perfluorophosphonic acid; 6:2FTSA, 6:2 fluorotelomer sulfonic acid; PFUnDA, perfluoroundecanoic acid; PFCA, perfluoroalkyl carboxylic acid; PFPeS, perfluoropentane sulfonate; PFSA, perfluoroalkyl sulfonate; PFDoA, perfluorododecanoic acid; PFBuS, perfluorobutane sulfonate; THPFOS, 1H,1H,2H,2H perfluorooctane sulfonate; PFTDA, perfluorotetradecanoic acid; PFOSA, perfluorooctane sulfonamide; PFAA, perfluoroalkyl acid

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dietary intake was the main exposure pathway to PFOS and PFOA, followed by the consumption of drinking water (Ericson et al., 2008b). In turn, dust and air (indoor environment) would mean only a minor contribution, with less than 1% and 2% for PFOS and PFOA, respectively (Ericson Jogsten et al., 2012).

Although during the last decades the use of PFAS has been very wide and widespread, only until relatively few years ago, there had been no special concern regarding the human exposure to these chemicals, as well as their potential adverse health effects. An evidence of this is the small number of scientific publications. For example, searching the terms "perfluorinated compounds" and "human exposure" in Scopus (www.scopus.com), the first indexed paper was published in 1998, whereas only one paper was also indexed in 1999 and in 2003. Only until 2006, the number of indexed papers did not reach the two digits (11), but in 2007 this figure was already doubled (23). In the current decade, the annual number of published scientific manuscripts on the topic "human exposure to perfluorinated compounds" has never been less than 30. A similar tendency is also found when the term of search "perfluorinated compounds" is replaced by the most currently used "PFAS". The first two papers correspond to 2001, but in 2018 the number of indexed papers on "human exposure to PFAS" reached 98. Similar data have been found using the same search terms in PubMed (www.ncbi.nlm.nih.gov/pubmed).

In a study conducted in 2007, we found that, in certain cases, drinking water could be a source of exposure to PFAS as important as the dietary intake of these chemicals (Ericson et al., 2008a). Recently, we reviewed the scientific literature regarding the occurrence and levels of PFAS in food and the human dietary intake of these chemical (Domingo and Nadal, 2017). Based on the available data, at least for the most well studied compounds (PFOS and PFOA), we concluded that the potential human health risks should not be of concern for non-occupationally exposed individuals. In order to have a more completed and updated information on human exposure to PFAS, the present review was aimed at assessing the current state of the art on the concentrations of PFAS in drinking water over the world, with special attention to PFOS and PFOA. The period of this review has covered just the last 10 years, being focused only on scientific publications found in the databases Scopus and PubMed. Next, we summarize the available information on the concentrations of PFAS in drinking/tap water and, when estimated, the intake by the general population of a number of countries.

2. Europe

2.1. France

In the current decade, the first data in France were reported by Boiteux et al. (2012). These authors conducted a study aimed at determining the occurrence of PFOA, PFOS, PFBA, PFBS, PFHxS, PFHxA, PFPeA, PFHpA, PFNA and PFDA in 331 and 110 samples of raw and treated water, respectively, which were collected in the summer of 2009 and in June 2010. PFOS, PFHxS, PFOA, and PFHxA were the most frequently detected PFAS in raw water, with the sum of PFHxS, PFBS and PFOS, representing 53% of the total concentrations measured in raw-water samples. PFHxA was the compound showing the highest concentration (139 ng/L). When that study was carried out, there were no national/EU regulations regarding maximum levels of PFAS in drinking water. However, some agencies had issued guidelines on maximum allowable levels. For example, the Drinking Water Commission of the German Ministry of Health deduced a strictly health-based guidance value for safe lifelong exposure for all population groups of 300 ng/L for combination of PFOA and PFOS in drinking water (Trinkwasserkommission, 2006), while a health-based drinking water concentration protective for lifetime exposure of 40 ng PFOA/L was developed by means of a risk-assessment approach by the New Jersey Department of Environmental Protection (Post et al., 2009), while the USEPA developed provisional health advisory short-term values for PFOS and PFOA of 200 and 400 ng/L, respectively. In this sense, Boiteux et al. (2012) found that the highest concentrations of PFOS and PFOA (22 and 12 ng/L, respectively), were well below the guidelines proposed in the US and Germany. On the other hand, Le Coadou et al. (2017) measured the presence of various emerging contaminants –including 10 PFAS- in 40 brands of bottled packaged spring waters (SPW), or natural mineral waters (NMW), sold in France, which corresponded in volume to 70% of the French bottled water. Six PFAS were quantified in a range of 0.6–9.5 ng/L in 4 samples, with Σ PFAS not exceeding 20 ng/L (mean: 6.7 ng/L, median: 3.4 ng/L; n = 4). The detection frequencies of PFAS in the 40 brands of bottled water were the following: PFOS (10%), PFHxS (5%) and PFBS (2.5%). However, PFPA, PFHxA, PFNA and PFDA could not be detected.

Recently, Bach et al. (2017) performed a study with various objectives focused on identifying the PFAS discharged into a French river by two fluoropolymers manufacturing plants, and on assessing the impact of the recent and past PFAS contamination on the water quality of two wellfields located along the river. It was estimated that 4295 kg of PFHxA, 1487 kg of 6:2FTSA, 965 kg of PFNA, 307 kg of PFUnDA, and 14 kg of PFOA were discharged in the river by the two facilities in 2013. The impact on the water quality of the drinking water resources was evidently demonstrated, being the total PFAS levels the highest reported in France until that date. The total PFAS concentrations in the treated water ranged between 86 and 169 ng/L, being clearly high, although not exceeding the available guideline values. Taking into account that drinking water is a route of exposure for populations using water contaminated by PFAS discharges, in a subsequent study performed by the same research group (Boiteux et al., 2017), it was shown that conventional drinking water treatments such as aeration, sand or granular activated carbon filtration, ozonation or chlorination did not efficiently remove PFAS. An increase in the concentration of certain PFAS was even observed after ozonation, while only nano-filtration was able to remove all the analyzed PFAS. In the treated water, total levels of PFAS never exceeded 60 ng/L.

Schwanz et al. (2016) determined the levels of 16 PFAS in 38 bottled waters and 58 samples of tap water from France and two other countries, Brazil and Spain. The profile of compounds in the samples of bottled water was significantly different for the three countries. Thus, PFOS was only detected in France (26% of the samples), while PFBS was detected in France and Brazil, but not in Spain. In contrast, Spain was the only country where PFHxA was quantified in 20% of the samples. FOSA was quantified in bottled waters from Brazil, being in general the median concentrations of the total PFAS slightly higher than those in samples of France and Spain. The median concentration of the total PFAS in bottled water was the following: Brazil > France > Spain, with 15.0, 14.9 and 11.3 ng/L, respectively. However, the highest level of contamination in a single sample corresponded to a bottled water sample of France, with 116 ng/L (the sum of all individual PFAS). Anyway, it was concluded that in none of the 3 investigated countries, drinking water would mean an imminent human health risk due PFAS contamination.

2.2. Germany

In the decade of the 2000, some studies regarding the levels of PFAS in drinking waters of Germany were published. Skutlarek et al. (2006) measured the concentrations of 12 PFAS in water samples collected in the Rhine River and its main tributaries, as well as in the Moehne River, canals, and drinking waters of the Ruhr catchment area. The results, corresponding to the samples of drinking water in samples of the Ruhr and Moehne area, showed that the major component was PFOA (519 ng/L), followed by PFHpA (23 ng/L) and PFHxA (22 ng/L). All measured levels (sum of 7 detected components) in the Rhine River and its main tributaries were below 100 ng/L. The maximum concentration of all drinking water samples in the Rhine-Ruhr area was 598 ng/L. An

interesting conclusion was that the levels of PFAS in drinking waters decreased in parallel to raw water samples along the flow direction of the Ruhr River. However, these levels were not significantly different from those in surface water, ultimately suggesting that PFAS were not successfully removed by water treatment steps. In turn, Lange et al. (2007) measured the levels of PFAS and PFCA in German surface waters and bank filtrates used for drinking water production. A number of surface waters, used as drinking water sources for millions of people in Germany, were analyzed for PFAS (C4–C10 homologues) and PFCA (C6–C14 homologues). In the Rhine, the highest concentrations corresponded to PFBS, with a maximum of 2.8 mg/L. The concentrations of the rest of PFAS were considered as background levels. Finally, in the drinking water from the Lake Constance, only PFOS and PFOA could be detected at concentrations of 3 and 1 ng/L, respectively.

Hölzer et al. (2008) and Wilhelm et al. (2009) reported the results of a biomonitoring study carried out in September-November 2006 aimed at determining the concentrations of PFAS in blood plasma of subjects living in Arnsberg (Sauerland, Germany), who had been affected by PFOA contamination of public water supplies. The potential association between drinking-water consumption and the concentrations of PFAS in plasma was also investigated. Samples were analyzed for PFOS, PFHxS, PFBS, PFOA, PFHxA and PFPA. Among the analyzed PFAS, PFOA was the main compound in drinking water (500–640 ng/L). The consumption of tap water was associated with raised PFOA concentrations in plasma. Participants reporting daily intakes of tap water higher than 1.5 L showed a 2-fold increase in the PFOA plasma levels, compared with those who reported to drink < 0.25 L/day. The importance of tap water in human exposure to PFAS –and more specifically to PFOS and PFOA-was clearly demonstrated. It was noticed that the concentrations of PFAS in plasma of children and adults drinking PFAS-contaminated water increased 4- to 8-fold, compared with controls. Further studies in the area were conducted. The introduction of charcoal filtration in July 2006 reduced PFOA concentrations in drinking water, which was reflected in the results of the one-year follow-up study on the PFOA plasma levels in residents from Arnsberg, with a 10–20% reduction. When a two-year follow-up study was performed (Brede et al., 2010), plasma concentrations of PFOA, PFOS and PFHxS decreased in the residents from Arnsberg. Wilhelm et al. (2010) reported the occurrence of PFAS in drinking water and drinking water resources in North Rhine-Westphalia for the sampling period 2008–2009. Based on the different approaches, the authors suggested these provisional health-related indication values as safe in drinking water for life-long exposure: PFBA 7 μg/L, PFPA 3 μg/L, PFHxA 1 μgL, PFHpA 0.3 μg/L, PFBS 3 μg/L, PFPeS 1 μg/L, PFHxS 0.3 μg/L, and PFHpS 0.3 μg/L.

Llorca et al. (2012) analyzed the occurrence of 21 PFASs in 148 samples from the whole water cycle (ultrapure water, tap water, and treated wastewater) of Germany and Spain. Regarding tap water, in the Spanish samples a greater number of PFAS was detected, being the most frequently found PFBA (52%), PFPeA (38%), PFOA (37%), PFBS (35%), PFHxS (36%) and PFOS (51%). In the samples of tap water collected in Germany, PFHxA (80%), PFHpA (100%) and PFOA (40%) were the most frequently detected PFAS. The concentrations in Spanish tap water were higher than those in German samples, being PFOS the most relevant compound (0.19–258 ng/L), while PFBA, PFPeA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFBS and PFHxS were also detected. In contrast, the highest concentrations of PFAS in German samples corresponded to PFHpA (0.23–24 ng/L). With respect to bottled water, PFAS were found in two of the six commercial brands that were analyzed. PFHpA levels in these samples were 6.6 and 12 ng/L, while in one of them PFOS was also found (1.0 ng/L). On the other hand, Ullah et al. (2011) simultaneously determined the concentration of various PFPAs, PFCAs and PFSAs in tap water samples from five European countries (Belgium, Italy, The Netherlands, Norway and Sweden), in addition to Germany. The highest concentration corresponded to PFBS (18.8 ng/L) and PFOA (8.6 ng/L) in samples collected in Amsterdam, and to PFOS (8.8 ng/L) in a tap water sample from Stockholm. PFPAs were not detected, with the exception of PFOPA in two water samples from Amsterdam, at levels close to the LOD (0.095 ng/L).

Gellrich et al. (2013) analyzed the levels of a number of PFAS in various sources of water intended for human consumption, including 119 mineral waters, 26 tap water samples, 18 spring water samples and 14 raw (untreated) water samples. PFAS concentrations were detected (LOD, 1 ng/L) in 52% of all samples, with the highest concentration (sum of PFASs), 42.7 ng/L, found in tap water. In turn, Fromme et al. (2017) quantified the body burden of an adult population exposed to 7 PFASs through drinking water, who lived next to, or apart from, a former production plant of PFOA in South Bavaria. Plasma samples were also collected in 2014 and 2016 in Munich, a city without noticeable PFAS contamination in drinking water. The highest concentration of PFOA was found close to the facility (85.5 μg/L), while in the control area, the level was considerably lower, 2.4 μg/L. The highest 95th percentile levels were 13.5 μg/L for PFOS, 3.0 μg/L for PFNA, and 1.5 μg/L for PFHxS.

2.3. Italy

In a three-year monitoring campaign (2010–2013), Castiglioni et al. (2015) investigated the occurrence, sources and fate of 9 PFCA and 3 PFSA, in different aquifers of the River Lambro basin, which runs through the most urbanized and industrialized area of Italy. The results confirmed that PFAA are ubiquitous contaminants in aqueous environments, being identified the main sources and the environmental fate of these chemicals in the area. Despite the ubiquitous contamination of groundwater by PFAA, they were well removed by the drinking water treatments adopted in the city of Milan. Concentrations measured in distributed drinking waters were very far from the proposed threshold values. Therefore, there was no risk for the consumers in a short term exposure. In a study performed to monitor the levels of PFAS in waters from European rivers, it was found that the river Po (northern Italy) showed the highest concentrations of PFOA, being PFASs contamination also important in other Italian rivers. This contamination involved also drinking water where 9 PFCAs (PFBA, PFPeA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFUnA and PFDoA) and 3 PFSAs (PFBS, PFHxS and PFOS) were detected (Ingelido et al., 2018). The contamination of drinking water was found to be the main factor influencing PFAS serum levels. After stratification by ULSS (Unità Locale Socio Sanitaria), the correlation between tap water consumption and serum PFAS concentrations became direct and significant for PFOA and PFNA in ULSS 5, and for PFHpA and PFOS in ULSS 6 (Ingelido et al., 2018). Recently, Mastrantonio et al. (2018) reported the results of an ecological study, which was the first epidemiological investigation conducted in Italy on a population living in an area contaminated by PFAS in drinking water, and possibly affecting the food chain. In Italy, there was no limit for the concentrations of PFAS in drinking water. In January 2014, after the detection of an important water contamination (surface, underground and drinking water) in an area of the Veneto Region, the Italian National Health Institute (ISS) established the maximum levels of PFAS in drinking water in order to protect people from potential health risks. These levels were the following: PFOS ≤30 ng/L, PFOA ≤500 ng/L, and other PFAS ≤500 ng/L. The main cause of PFAS contamination in these zones was due to the draining of fluorinated chemicals from a manufacturing company, which was operating in Trissino (Vicenza Province) since 1964. The area contaminated by PFAS included 24 municipalities. Higher mortality levels (for some causes of death), potentially associated with PFAS exposure, were detected in the contaminated municipalities (Mastrantonio et al., 2018).

2.4. Sweden

In 2012, drinking water contaminated with PFAS, basically PFOS and PFHxS, was confirmed in Uppsala (Gyllenhammar et al., 2015). In a

pilot study, nine drinking water samples were collected from different areas of that city for PFAS analysis. The results showed that drinking water was contaminated with PFHxS, PFOS, PFBS, PFHxA and PFOA in parts of Uppsala. PFHxS and PFOS concentrations between 25 and 45 ng/L were detected in the contaminated water. A first study examined the influence of this water on the concentrations of PFASs in human serum. It was found that exposure to drinking water was the determining factor behind the increasing temporal trends of PFBS and PFHxS levels in serum -sampled between 1996 and 2012- from young women. In contrast, the levels of PFOA and PFOS in the drinking water were not sufficiently high to change the commonly observed decreasing trends of serum levels for these compounds. It was suggested that other sources had been more important for exposure to PFOA and PFOS than drinking water (Gyllenhammar et al., 2015). Because of that episode in Uppsala, various longitudinal cohort studies have been conducted in the current decade in order to assess possible associations between the levels of PFAS detected in drinking water and their concentrations in the population-based cohort. In serum samples collected from an Uppsala Seniors (PVIUS) cohort (70–80 years), where the age and location were the same for all the individuals, the concentrations of PFHxS, PFUnDA, PFNA and PFDA showed significant increases, while those of PFOSA, PFHpA, PFOS, and PFOA significantly decreased (Stubleski et al., 2016). Contrasting with the results of other investigations, PFHxS concentrations showed the highest increase, which was probably due to the local drinking water contamination incident. At the same time, individuals maintaining the same zip code throughout the study were divided into a reference (without known PFAS exposure), low, intermediate, and high exposure areas, depending on the proportion of contaminated drinking water. Eight PFAS were evaluated for significant changes in temporal PFAS concentrations. The levels of PFHxS in plasma showed significant increases in those subjected living in the zones with the highest percentage of contaminated drinking water. In contrast, PFOS showed an overall decrease, while the trend of other PFAS plasma concentrations did not show an association to the quality of the drinking water consumed (Stubleski et al., 2017).

In 2013, very high concentrations of PFOS and PFHxS wre detected in the drinking water of one of the two main suppliers of municipal water in Ronneby, Sweden (Li et al., 2018). During the period 2014–2016, 3418 individuals living in that municipality participated in a study aimed at determining the rates of decline in the serum levels of PFHxS, PFOS and PFOA, as well as their corresponding half-lives, after the end of a period exposure to drinking water contaminated by these PFAS. Clean water was provided from December 2013. Municipal drinking water in one-third of the households in Ronneby had been potentially contaminated since the mid-1980s. The estimated half-life for PFHxS was considerably longer than that for PFOA and PFOS (Li et al., 2018). Moreover, Andersson et al. (2019) investigated the potential relationship between the historical exposure to PFASs through drinking water and the incidence of thyroid disease in the general population of Ronneby, with long-term high exposure to PFHxS, PFOS, and to a lesser extent PFOA. No consistent patterns of increased risks of clinically detected thyroid diseases (hypothyroidism or hypothyroidism) were found in men or women living in Ronneby.

On the other hand, Gobelius et al. (2018) assessed 26 PFAS in the Swedish aquatic environment including surface water (n = 279), groundwater (n = 161), landfill leachate (n = 10), STP effluents (n = 13), and reference lakes (n = 10) for implications for Environmental Quality Standard (EQS) and drinking water guidelines, with focus on hot spots and drinking water source areas. One of the specific objectives was to compare measured PFAS concentrations with guideline values. The drinking water guideline value of 90 ng/L for Σ_{11}PFASs (PFBA, PFPeA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFBS, PFHxS, PFOS, and 6:2 FTSA) recommended by the Swedish EPA was exceeded in 3% of the samples from drinking water sources. While the Swedish and Danish drinking water guideline values (90 and 100 ng/L for Σ11PFASs and Σ12PFASs, respectively), were exceeded in a few cases, no drinking water sample from that study exceeded the drinking water recommendations from the US EPA, United Kingdom, The Netherlands and Germany. In another study on micropollutants in drinking water, the levels of PFAS did not exceed acceptable levels. The limit value for Σ11PFASs is 90 ng/L compared to the 7.5 ng/L found in that study (Tröger et al., 2018).

Banzhaf et al. (2017) reviewed the potential sources for PFAS in the drinking water supplies in Sweden, comparing the different occurrences of PFAS in raw and drinking water. PFAS were found at different concentrations, which would potentially affect the consumption of drinking water for more than 3.6 million inhabitants. While some sources were clearly identified, the authors noticed that much was still to be done in order to get a total understanding of the current situation in Sweden. In a on the behavior and fate of PFAS review in drinking water treatment (Rahman et al., 2014), it was already concluded that drinking water was a major source of exposure to short-chain PFAS.

2.5. Spain

In 2007, we initiated in our laboratory a program aimed at investigating the main sources of human exposure to PFAS. In one of the initial studies, we estimated the intake of PFOS, PFOA, PFHpA, PFBuS, PFHxS, THPFOS, PFDS, PFHxA, PFNA, PFDA, PFUnDA, PFDoA, PFTDA and PFOSA through drinking water (tap and bottled) by the population of Tarragona Province (Catalonia, Spain) (Ericson et al., 2008a). In tap water, the concentrations ranged 0.39–0.87 ng/L, and 0.32–6.28 ng/L for PFOS and PFOA respectively. PFHpA, PFHxS, and PFNA were also detected. The concentrations of PFAS were notably lower in bottled water, in whose samples even PFOS could not be detected. Assuming a human water consumption of 2 L/day, the daily intake of PFOS and PFOA by the population of the area under evaluation was estimated to be 0.78–1.74, and 12.6 ng, respectively). Based on these results, we concluded that drinking water might be a source of exposure to PFAS, at least as important as the dietary intake of these pollutants (Ericson et al., 2008b). In February 2008, again we collected municipal drinking water samples at 40 sampling points of Catalonia. These points were selected in accordance with the recommendations of the Catalan Agency of Public Health, including the most important supply areas of Catalonia (Ericson et al., 2009). The concentrations of the following 13 PFAS were analyzed: PFBuS, PFHxS, PFOS, THPFOS, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFUnDA, PFDoDA, PFTDA and PFOSA. Detection limits ranged between 0.02 (PFHxS) and 0.85 ng/L (PFOA). PFOS and PFHxS were the most frequently detected compounds: 35 and 31 samples, being the maximum concentrations 58.1 and 5.30 ng/L, respectively. In turn, PFBuS, PFHxA, and PFOA were also frequently detected (29, 27, and 26 samples, respectively), being their maximum concentrations 69.4, 8.55, and 57.4 ng/L, respectively. However, PFDoDA and PFTDA were not detected in any sample. According to those data, the concentrations of PFOS and PFOA found in drinking water from Catalonia should not pose human health risks. However, because information on safety limits for exposure to the remaining PFAS was not available, we concluded that for guidance purposes that information is essential (Ericson et al., 2009). In the last survey performed in our laboratory, we analyzed the concentrations of 15 PFAS in water samples collected in Catalonia at three stages of the drinking water treatment process in various water purification plants with advanced water treatment technologies. The study was designed considering different stages through the drinking water distribution: 1) at the place of abstraction (raw water), 2) after the process transforming raw water into drinkable water, and 3) in the places of consumption (public fountains) (Domingo et al., 2012). The highest mean levels corresponded to PFOS and PFOA: 1.81 and 2.40 ng/L, respectively. The levels of PFDS and PFTDA were under their detection limits in all the samples. The most relevant conclusion of that survey was that, although the treatment processes caused slight reductions in concentrations of PFAS, these processes did not cause significant changes in the quantities

of the compounds that are already contained in the raw water.

Flores et al. (2013) studied the occurrence of PFOA and PFOS in the Llobregat River (Catalonia, Spain), which supplies raw surface water to the Barcelona's drinking water treatment facility, as well as their removal during the purification process. A total of 131 samples were collected between 2002 and 2012. Trace levels of PFOS (3.0–21 ng/L) and PFOA (< 4.2–5.5 ng/L) that were detected in treated drinking water, were significantly lower with respect to those found in previous years, while human health risks were not expected. These concentrations represented mean removal efficiencies of 89% and 86% for PFOA and PFOS, respectively.

On the other hand, the levels of PFAS in drinking waters from Spain have been compared with those in Germany (see above: Llorca et al., 2012), and with those in France and Brazil (see above: Schwanz et al., 2016). The authors of both studies concluded that, despite the high levels found in Brazil, in none of these countries, PFAS contamination in drinking water would mean associated health risks.

2.6. Other European countries (Norway, Belgium, Faroe Islands)

To the best of our knowledge, to date in Norway only a single study has determined the concentrations of PFAS in drinking water. Haug et al. (2010) analyzed the levels of 16 PFAS in 3 samples of drinking water (1 L each), which were collected from the tap in households receiving water from different suppliers. PFOA was the dominating PFAS, with concentrations of 0.65, 1.2 and 2.5 ng/L in the analyzed samples. The concentrations of PFOA in drinking water were 16–63 times below a health-based drinking water concentration protective for lifetime exposure set to 40 ng/L (Post et al., 2009). Although the 3 samples were collected in the greater Oslo area, a relatively large difference in concentrations between them was observed for the PFCAs. On the other hand, in Flanders (Belgium), Cornelis et al. (2012) determined the levels of PFOS and PFOA in various matrices including 4 tap water samples collected in 2008 of different water suppliers. Concentrations of PFOS and PFOA were detected in drinking water, but their contribution to human exposure was less than 1%. In the Faroe Islands, Eriksson et al. (2013) analyzed 15 PFASs, 11 PFCAs and 4 PFSAs, in samples –collected in 2011-2012- of various food items and drinking water. The contamination of PFASs in drinking water (and also in food) was overall low. The highest PFBA levels in water was 1.2 ng/L, which was found in untreated water from Kornvatn, followed by 0.82 ng/L in the drinking water from the same location. No exposure assessment was performed in that study.

3. America

3.1. USA

The most investigated episode on contamination of drinking water by PFAS, whose exposure affected the US general population, occurred in the Mid-Ohio Valley. Drinking water in six water districts of two states was contaminated by PFOA, which had been released by a nearby DuPont chemical facility near Parkersburg, West Virginia (Bartell et al., 2010). The average PFOA concentration in one (Little Hocking) of the system distribution water (January 2002–May 2005) was reported to be 3.55 ng/mL (range 1.5–7.2 ng/mL), whereas for private wells used by study participants, PFOA concentrations ranged from not detectable (< 0.010 ng/mL) to 14.0 ng/mL (Emmett et al., 2006). The chemical plant had started to use PFOA in manufacturing fluoropolymers in 1951. As a direct consequence of the contamination of drinking water, a project known as the C8 (PFOA) Health Project was created, authorized and funded as part of the settlement agreement reached in the case of *Jack W. Leach* et al. *v. E.I. du Pont de Nemours & Company* (no. 01-C-608 W.Va., Wood County Circuit Court, filed 10 April 2002) (Frisbee et al., 2009). For the project, two cohorts were formed. Participants were interviewed for 2008–2011 with respect to demographics, health-related behaviors, as well as histories of potential chronic diseases (Winquist et al., 2013). In relation to this episode, a number of studies have been conducted in recent years. They have been mainly focused on two issues: a) to corroborate the relationship between the consumption of PFOA-contaminated drinking water and the serum levels of PFOA in the study population (Frisbee et al., 2010; Herrick et al., 2017; Hoffman et al., 2011; Seals et al., 2011, Steenland et al., 2009), and b) to establish potential associations between PFOA -and other PFAS- and health effects among highly exposed Mid-Ohio Valley community residents and workers (Barry et al., 2013; Darrow et al., 2013; Savitz et al., 2012; Stein et al., 2013, 2014a,b; Steenland et al., 2018).

In 2007, two highly contaminated water districts began to filtrate water using granular activated carbon, being the rate of decline in serum PFOA determined during the first year of filtration (Bartell et al., 2010). The average rate of decrease in the concentration of PFOA in serum was 26% per year. In turn, Herrick et al. (2017) measured PFOA and other 10 PFAS in 1608 serum samples from 931 Mid-Ohio River Valley residents. While these residents appeared to have blood concentrations of PFOA higher than the average US levels, none of the remaining PFAS analyzed in serum were detected above mean US population concentrations. On the other hand, the human health effects derived from consumption of PFOA-contaminated drinking water showed different results, with positive and negative evidences on the association of measured PFOA (and other PFAS) and the assessed effects (Barry et al., 2013; Savitz et al., 2012; Stein et al., 2013, 2014a,b; Darrow et al., 2013; Steenland et al., 2018).

Another important series of studies on the occurrence and potential significance of PFAS in general -and PFOA in particular-in drinking water systems has been carried out under the auspices of the New Jersey Department of Environmental Protection. After detecting PFOA in two New Jersey (NJ) public water systems (PWS) at levels up to 190 ng/L, a study on the concentrations of PFOA in 23 other NJ PWS was conducted in 2006 (Post et al., 2009). This chemical was detected in 15 of the systems at concentrations between 5 and 39 ng/L. PFOA was commonly found in raw and finished water from NJ PWS, using both surface and groundwater sources. It was concluded that according to the relationship between the levels of PFOA in drinking water and the concentrations of PFOA in human serum in humans, drinking water concentrations such as those detected in NJ might substantially contribute to the total exposure to PFOA. PFOA in most NJ PWS was below the health-based concentration, but various New Jersey PWS exceeded that concentration (Post et al., 2009). In a subsequent study, Post et al. (2013) determined the occurrence of PFOA, PFOS, and other 8 PFAS in raw water samples from 18 ground water and 12 surface water from 29 additional NJ PWS. Between 1 and 8 PFAS were detected (≥ 5 ng/L) in 21 (70%) of 30 PWS samples, at total concentrations of 5–174 ng/L. PFOA was the most commonly detected compound (57% of samples), being found at the highest maximum level (100 ng/L). Some of the highest concentrations of other PFAS were at sites with little or even no PFOA. In that study, PFOA was detected more frequently (30%) and at higher concentrations (up to 96 ng/L) than in raw or finished drinking water elsewhere.

On the other hand, in an exhaustive review on the role of PFOA as an emerging contaminant of drinking water, Post et al. (2012) reported that a continued exposure to even relatively low concentrations of this compound in drinking water could substantially increase total human exposure, with a serum/drinking water ratio of about 100/1. Therefore, exposure to drinking water concentrations of 10, 40, 100, or 400 ng/L could increase mean serum levels by about 25%, 100%, 250% and 1000%, respectively, from the general population background serum level of about 4 ng/mL. Exposure to relatively low drinking water concentrations of long-chain PFAA might notably increase human body burdens, which would remain elevated for many years after the end of the exposure. Consequently, an important benefit of addressing exceedances of PFAA drinking water guidelines is that treatment removal processes aimed at removing the chemical(s) of concern can also

partially -or totally-remove other PFAA and PFAS, as well as unrelated contaminants, which could be present at concentrations of concern for public health (Post et al., 2017). It is important to note that PFAAs for which there are drinking water guidelines may also co-occur with other PFAS that are not included in routine analysis, and therefore, they are only detected by specific research analytical methods (Post et al., 2017). Regarding PFOS, based on immunosuppression in mice, a reference dose (RfD) of 1.8×10^{-6} mg/kg/day was recently estimated for chronic human exposure to PFOS (Pachkowski et al., 2019). The comparison of this RfD to the PFOS RfD derived by the USEPA Office of Water, suggested to the authors that this last RfD would not provide sufficient protection against the potential adverse health effects of PFOS (Pachkowski et al., 2019).

Other recent studies conducted in the USA have also reported the presence of PFAS in public drinking water in Cape Cod, MA (Schaider et al., 2014), as well as in 20 source waters located in the states of Wisconsin (1), Oklahoma (1), Alaska (1), California (2), Alabama (1), Colorado (2), Ohio (1), Nevada (1), Minnesota (1) New Jersey (9) (Appleman et al., 2014), and Rhode Island (Guelfo et al., 2018). In New Hampshire, for example, Daly et al. (2018) found significant high concentrations of PFOS, PFOA, and PFHxS in serum samples of the population exposed to contaminated drinking water, being consistent with PFAS drinking water contamination. More recently, Hu et al. (2019) measured the concentrations of 15 PFAS in home tap water samples collected in 1989–1990 from 225 participants in a nationwide prospective cohort of U.S. women: the Nurses' Health Study (NHS). It was found that tap water PFOA and PFNA were statistically significant predictors of plasma concentrations among those individuals consuming daily tap water.

3.2. Canada

D'eon et al. (2009) determined the levels of new class of perfluorinated acids, the perfluorinated phosphonic acids (PFPAs), in an urban watershed, where in 2007 water samples were collected from eight creeks and rivers within and surrounding the city of Toronto, Ontario. PFPAs at the urban sites were detected at concentrations similar to those at the agricultural sites, with only an exception, being found in 80% of surface water samples. These samples were also analyzed for the C8- to C11–PFCAs and PFOS. The ranges of concentrations were between less than the LOD (2100 pg/L) to 19,000 pg/L, less than the LOQ (< 125 pg/L) and 3000 pg/L, less than the LOQ (< 125 pg/L) and 2800 pg/L, ND (< 25 pg/L) and 1100 pg/L, and 560 and 80,000 pg/L, for PFOA, PFNA, PFDA, PFUnA and PFOS, respectively.

3.3. Brazil

Only few studies have examined the occurrence of PFCs in South America. With respect to drinking water, Quinete et al. (2009) measured the concentrations of 10 PFCs (0 PFCs, PFHxS, PFOS, PFDS, PFOSA, PFHpA, PFOA, PFNA, PFDA, PFUnDA, and PFDoDA) in samples collected from various districts in the Rio de Janeiro State (southeast Brazil). PFOS, PFOA, and PFHxS were found in all drinking water samples al levels ranging 0.58–6.70, 0.35–2.82 and 0.15–1.00 ng/L, respectively. In turn, PFHpA was detected in more than 90% of the samples at levels between < 0.1 and 2.21 ng/L, while the rest of analyzed PFCs were rarely detected. Based on these results and assuming a consumption of 2 L/day of water, the intakes of PFOS, PFOA, PFHxS, and PFHpA through drinking water were 3.4, 2.4, 0.74, and 0.96 ng/person/day, respectively.

4. Asia

4.1. China

Jin et al. (2009) collected tap water samples from 21 cities (55 sites) from various Chinese regions in order to determine the levels of PFOS and PFOA. Although in most cities the concentrations of these PFAS were relatively low, in Shenzhen and Guangzhou both compounds exceeded 10 ng/L. Also in China, Sun et al. (2011) measured the levels of PFAS in the Hun River, four canals, ten lakes, as well as influents and effluents from four main municipal wastewater treatment plants (WWTPs) in Shenyang. The levels in WWTP effluents were higher than those in surface waters, with values ranging 18.4–41.1 and 1.69–3.85 ng/L for PFOA and PFOS, respectively. Interestingly, the composition profiles of PFAS in surface waters was not consistent with those found in adult blood samples from Shenyang. This suggested a poor removal efficiency of PFAS from surface water to tap water. In order to better understand the contamination levels and removal mechanisms of PFAS during urban wastewater and drinking water treatment processes, Pan et al. (2016) determined the fate of 18 PFAS in urban water cycle in 3 WWTPs and 2 drinking water treatment plants (DWTPs) of Guangzhou city. Another objective of that study was to provide scientific basis for the optimization of treatment techniques. The average total PFAS concentrations in the WWTPs were 19.6–232 ng/L in influents and 15.5–234 ng/L in effluents. In the DWTPs, total PFAS concentrations were 4.74–14.3 ng/L in influents, and 3.34–13.9 ng/L in effluents. Therefore, PFAS found in tap water did not pose immediate human health risks in a short-term exposure.

Tan et al. (2017) determined the concentrations of 17 PFASs in tap water and surface waters of major rivers and lakes that serve as source of drinking water in Eastern China. Fifty-one water samples from 9 rivers, 45 samples from 9 lakes, and 64 tap water samples from 17 cities were analyzed. The total PFAS concentrations in tap water ranged from 1.4 to 175 ng/L, but the most worrying result was that PFOA concentrations (115–151 ng/L) found in tap water of three districts of Hangzhou exceeded the USEPA drinking water quality standard of 70 ng/L. The same research group also analyzed the concentrations of 17 PFAAs in samples of surface waters of the Qiantang River (Lu et al., 2017). The results were compared with those of surface water and tap water samples collected in Hangzhou and its adjacent areas in Eastern China. ΣPFAAs, whose levels ranged from 9.5 to 174.8 ng/L in samples of tap water, showed a similar PFAA composition profiles to that found for the surface waters, at a moderate/high levels of contamination, which would not mean human health risks.

Recently, Tian et al. (2018) analyzed 11 PFAS in 981 maternal blood samples of Shanghai collected at 12–16 weeks of gestation. Dietary factors, including drinking water, were assessed as potential determinants of PFAS concentrations in blood. High concentrations of total PFAS (mean: 130 ng/L) had been previously found in tap water from Shanghai (https://www.sciencedirect.com/science/article/pii/S0160412018302691?via%3Dihub; Mak et al., 2009). All PFAS concentrations were higher in pregnant women consuming tap water than in those drinking purified tap water, or barreled water. It was concluded that drinking water during pregnancy could contribute to higher exposure to PFAS, independent on other dietary factors, sociodemographic characteristics and lifestyle factors. In another recent study of the same research group (Zhou et al., 2019), the association of PFAS with diet and drinking water in pre-conception women was also examined in one of the highest polluted areas in China: Shanghai. Through questionnaires, participants were asked for the most common source of drinking water: tap water only, both tap water and bottled water, bottled water only, filtered water, and combination of tap water, bottled water and filtered water. In comparison with the women consuming mainly tap water, those reproductive aged women drinking bottled water showed significant decreases (between 9 and 13%) in the blood concentrations of PFHpA, PFDA, PFOA, PFUA and PFBS.

Zhang et al. (2019) analyzed the levels of PFOA and PFOS in 166 samples of drinking water collected across 28 Chinese cities. In 13 of these cities, PFOA and PFOS concentrations were determined in 847 human blood samples, which were collected in parallel with the samples of drinking water. The geometric mean levels of PFOA and PFOS in

drinking water were 2.5 and 0.7 ng/L, respectively, while the geometric mean blood concentrations were 2.1 and 2.6 ng/mL, respectively. The authors estimated the relative source contributions (RSCs) of drinking water to the total daily intake in China, which were 23% and 12.7% for PFOA and PFOS, respectively. Using the mean RSCs, Chinese health advisory values of 85 and 47 ng/L for PFOA and PFOS, respectively, were derived. In turn, in order to assess the occurrence, composition, and distribution of PFAAs in drinking water of China on a national scale, Li et al. (2019) determined the levels of 17 PFAAs in samples of drinking water from 79 Chinese cities, in 31 provincial-level administrative regions. The results showed that PFAAs were ubiquitous in drinking water across China, being the Σ_{17}PFAA in the range 4.49–174.93 ng/L, with a mean value of 35.13 ng/L. The geographic distribution of Σ_{17}PFAAs in drinking water was: Southwestern China (57.67 ng/L) > Eastern coastal China (32.85 ng/L) > Middle China (29.89 ng/L) > Northwestern China (28.49 ng/L) > Northeastern China (22.03 ng/L). Recently, various studies have been also conducted in order to get information on the occurrence, sources and levels of PFAS in soil, water and sediment from a major drinking water source in Tianjin (Cao et al., 2019), in groundwater and home-produced vegetables and eggs around a fluorochemical industrial park in Fuxin (Bao et al., 2019), and in water and fish from drinking water sources of Beijing (Meng et al., 2019). These studies complete the current exhaustive information on human exposure to PFAS in China.

4.2. Japan

Takagi et al. (2011) measured the levels of PFOS and PFOA in water samples collected at every stage in the drinking water treatment processes from several water purification plants, which were using advanced water treatment technologies in Osaka. Both PFAS were detected in all finished water samples at levels between 1.3 and 3.7 ng/L, and from 6.5 to 48 ng/L, for PFOS and PFOA, respectively. The values of PFOS and PFOA in samples collected after sand filtration and ozonation were similar to those found in raw water samples. It indicated that sand filtration, sedimentation, and ozonation had no effect on the removal of PFOS and PFOA, which by contrast were effectively removed by fresh activated carbon. On the other hand, Kaboré et al. (2018) examined the occurrence and levels of 29 PFAS in tap water from 41 cities from 9 countries: USA, Canada, Burkina Faso, Chile, Ivory Coast, France, Mexico, Norway and Japan. The mean levels of PFSAs and PFCAs ranged between < LOD to 3.9 ng/L in China (n = 3), USA (n = 2), Japan (n = 2), Ivory Coast (n = 11) and Burkina Faso (n = 16) tap waters. Seven samples were identified as outliers, including one from Japan, which presented much higher total PFAS concentrations (26 ng/L). It was concluded that according to the updated US EPA health advisory for PFOS and PFOA (70 ng/L), the samples of drinking samples collected in that worldwide study would not pose a health risk to consumers with respect to PFAA concentrations.

4.3. Other Asian countries (Afghanistan, India, South Korea)

Hemat et al. (2010) reported for the first time in Afghanistan, the concentrations PFOS and PFOA in samples of serum of children and adults living in Kabul city and in the rural area Ningarhar province-Shinwary district. In addition, drinking water samples were collected from 10 tap water and 16 well water sources. All PFOS and PFOA concentrations in drinking water were below their respective LOQs: 0.03 and 0.015 μg/L, for PFOS and PFOA, respectively. In India, Sharma et al. (2016) assessed 21 PFAS exposure patterns of drinking water resources used by local populations living in various locations along the Ganges River. An assessment of human exposure through drinking water consumption was also carried out. PFHxA and PFHpA could be detected in all samples ranging from 0.8 to 4.9 ng/L, and from 0.5 to 3.5 ng/L, respectively. The levels of other PFCAs such as PFPA, PFOA, PFNA, and PFDA ranged between < method quantification limit (MQL) – 2.2 ng/L[1], < MQL – 0.8 ng/L, < MQL – 0.2 ng/L[1], and < MQL – 0.1 ng/L, respectively. In the Seoul Metropolitan area (South Korea), Kim et al. (2019) collected samples of human serum, house dust, one-day composite food samples, drinking water, and hand wipes, in which the concentrations of 15 PFAS determined. In drinking water samples, the concentrations ranged between 0.370 and 10.8 ng/L (mean 2.71 ng/L), with 10 PFAS being detected in these samples. PFCAs, rather than PFSAs, were the dominant PFAS, being PFOA the most abundant compound, with concentrations between ND and 3.29 ng/L (mean 1.29 ng/L).

5. Africa

Data on contamination of drinking water by PFAS in African countries is very limited. Essumang et al. (2017) studied the occurrence and levels of 14 PFAS (PFCAs and PFSAs) in two selected rivers (Kakum and Pra Rivers) of Ghana, as well as in tap water obtained from those rivers. PFOA, PFOS, PFHxA, PFDA and PFPeA were commonly detected in rivers and tap water. The mean levels of Σ PFAAs in the Kakum and Pra Rivers were 281 and 398 ng/L, while the mean concentrations in the samples of tap water -supplied from the treatment of water from these two rivers-were 197 and 200 ng/L, respectively. PFOA and PFOS constituted about 99% of the Σ PFAAs. Some data from tap and bottled water of Burkina Faso and Ivory Coast are also available in the literature. These data were obtained in a study on the occurrence and levels of PFASs in samples of drinking water from various locations of 9 nine countries around the world (see above, Kaboré et al., 2018).

6. Australia

Thompson et al. (2011) evaluated the contribution of drinking water to the daily intake of PFAAs. Sixty-two samples were directly collected from the drinking water taps at 34 sampling locations. PFOS and PFOA were the most commonly detected PFAAs, with percentages of 49% and 44% of all samples, respectively. The highest concentration corresponded to PFOS (16 ng/L), followed by those of PFHxS and PFOA (13 and 9.7 ng/L), respectively. It was estimated that for PFOS and for PFOA, the average contributions from drinking water were 2–3%, with maximum values of 22% and 24%, respectively.

7. Summary and conclusions

In 2009, the US Office of Water (US EPA, 2009) developed Provisional Health Advisory values for PFOA and PFOS in order to assess potential risks from exposure to these chemicals through drinking water. The PFOA and PFOS Provisional Health Advisory values were 400 and 200 ng/L, respectively. More recently, the USEPA (2016) published PFOA and PFOS Drinking Water Health Advisories for the US population, including the most sensitive groups of subjects. These health advisory levels were established at 70 parts per trillion, which should offer a margin of protection throughout the entire lives from adverse health effects resulting from exposure to PFOA and PFOS in drinking water. However, in the USA a number of States have also established their own guidelines, not only for PFOA and PFOS, but even for other PFAS. Regarding this, Post et al. (2017) published recently an interesting paper on key scientific issues in developing drinking water guidelines for PFAS, while Cordner et al. (2019) have just published guideline levels for PFOA and PFOS in drinking water considering the role of scientific uncertainty, risk assessment decisions, and social factors. The authors examined PFOA and PFOS water guideline levels developed by the USEPA and state agencies to protect people drinking the water, and summarized how and why these levels differ. It was noticed that seven states have developed their own water guideline levels for PFOA and/or PFOS ranging from 13 to 1000 ng/L, compared to the USEPA Health Advisory of 70 ng/L for both compounds, either

individually or combined. The authors concluded that the current USEPA Health Advisory is not sufficiently protective.

In the European Union, the European Food Safety Authority (EFSA) has proposed lowering the current tolerable intakes of PFOS and PFOA in foods, after examining new human epidemiological evidences (EFSA, 2018). In 2008, the authority's panel on contaminants in the food chain (CONTAM Panel) established tolerable daily intakes (TDIs) of 150 ng/kg body weight for PFOS and 1500 ng/kg body weight for PFOA. The EFSA is now proposing a tolerable weekly intake of 6 and 13 ng/kg body weight for PFOS and PFOA, respectively. EFSA is also looking at other PFAS for possible human health risks. Results are expected to be published during 2019. Although to establish specifics limits to protect health risks derived from human exposure to PFAS through drinking water are not among the objectives of the EFSA, the European Commission (EC, 2016) has included PFOS in the list of priority hazardous substances, which must be monitored in the EU water bodies. Moreover, the UK Health Protection Agency in agreement with the Drinking Water Inspectorate for England and Wales (DWI, 2007) advises that the maximum acceptable concentration of PFOS in drinking water is 300 ng/L, and that the maximum acceptable level of PFOA in drinking water is 10,000 ng/L.

The data on the concentrations of PFAS in drinking water reviewed in the present paper considerably differ among the countries for which recent studies have been carried out. It is important to note that scientific data corresponding to countries such as the United Kingdom, the Netherlands, Ireland, Greece and many other countries of the EU are not available in the used databases, Scopus and PubMed. Information corresponding to Central and South American countries, and African countries, is very scarce or it does not exist at all, while in Asia most data correspond to China. Anyhow, in general terms and based on the toxicological information about PFAS that is available so far, and taking into account the above levels considered as acceptable for various regulatory institutions, the health risks for the regular consumers of municipal/tap water do not seem to be of concern. However, it must be highlighted that most of the information found in the scientific literature here reviewed corresponds to only two PFAS (PFOS and PFOA), while the published data on other PFAS, as well as on their safety levels to protect human health, are scarce.

Although food, drinking water and air/dust are the main sources of PFAS exposure for non-occupationally exposed populations, it must be taken into account that the production of PFOS and PFOA is already banned in a number of countries. Consequently, it would be logical to expect less exposure to PFAS in the next few years. Meanwhile, it is important to fill the important number of gaps still existing, which include toxicological information on a notable series of PFAS, other than PFOS and PFOA, for which this information is in fact inexistent. Furthermore, given that humans are exposed to a mixture of PFAS, rather than to individual substances, the joint effects of PFAS should be understood better. Altogether, it would allow establishing more accurate guideline levels for PFAS in food and drinking water. Studies in those countries where there is not information on human exposure to PFAS through drinking water would be also of special interest.

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