Toxicology Reports 12 (2024) 436–447

Contents lists available at ScienceDirect

Toxicology Reports

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

Emerging contaminants in food matrices: An overview of the occurrence, pathways, impacts and detection techniques of per- and polyfluoroalkyl substances

Chukwuebuka Gabriel Eze[a,b], Emmanuel Sunday Okeke[f,g,*], Chidiebele Emmanuel Nwankwo[i,j,**], Raphael Nyaruaba[c], Uttpal Anand[d], Onyekwere Joseph Okoro[e], Elza Bontempi[h]

[a] Department of Science Laboratory Technology, Faculty of Physical Sciences, University of Nigeria, Nsukka, Enugu State 410001, Nigeria
[b] Institute of Biological Environmental and Rural Science Aberystwyth University, Wales, United Kingdom
[c] CAS Key Laboratory of Special Pathogens and Biosafety, Center for Biosafety Mega-Science, Wuhan Institute of Virology, Chinese Academy of Sciences, Wuhan, 430071, China
[d] CytoGene Research & Development LLP, K-51, UPSIDA Industrial Area, Kursi Road (Lucknow), Dist.– Barabanki, 225001, Uttar Pradesh, India.
[e] Department of Zoology and Environment Biology, Faculty of Biological Sciences, University of Nigeria, Nsukka, Enugu State 410001, Nigeria
[f] Department of Biochemistry, Faculty of Biological Sciences & Natural Science Unit, School of General Studies, University of Nigeria, Nsukka, Enugu State 410001, Nigeria
[g] Institute of Environmental Health and Ecological Security, School of the Environment and Safety, Jiangsu University, 301 Xuefu Rd., Zhenjiang, Jiangsu 212013, China
[h] INSTM and INSTM and Chemistry for Technologies Laboratory, University of Brescia, via Branze 38, Brescia 25123, Italy
[i] Department of Microbiology, Faculty of Biological Sciences & Natural Science Unit, School of General Studies, University of Nigeria, Nsukka, Enugu State 410001, Nigeria
[j] School of Food and Biological Engineering, Jiangsu University, 301 Xuefu Rd., Zhenjiang, Jiangsu 212013, China

ARTICLE INFO

Handling Editor: Prof. L.H. Lash

Keywords:
Per-and polyfluoroalkyl substances
Food matrices
Food contact materials
Toxicity
Remediation technology
Analytical techniques

ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) have been used in industrial and consumer applications for ages. The pervasive and persistent nature of PFAS in the environment is a universal concern due to public health risks. Experts acknowledge that exposure to high levels of certain PFAS have consequences, including reduced vaccine efficacy, elevated cholesterol, and increased risk of high blood pressure. While considerable research has been conducted to investigate the presence of PFAS in the environment, the pathways for human exposure through food and food packaging/contact materials (FCM) remain unclear. In this review, we present an exhaustive overview of dietary exposure pathways to PFAS. Also, the mechanism of PFAS migration from FCMs into food and the occurrence of PFAS in certain foods were considered. Further, we present the analytical techniques for PFAS in food and food matrices as well as exposure pathways and human health impacts. Further, recent regulatory actions working to set standards and guidelines for PFAS in food packaging materials were highlighted. Alternative materials being developed and evaluated for their safety and efficacy in food contact applications, offering promising alternatives to PFAS were also considered. Finally, we reported on general considerations and perspectives presently considered.

1. Introduction

Healthy food is necessary for sustaining human life by providing essential nutrients and energy needed for growth and development. Despite the rise in foodborne diseases, many food chain personelle worldwide fail to fully comprehend the significance of food safety. Several emerging contaminants including [27,72,70,74,2,69,84,81,16] microplastics; tetrabromobisphenol A (and its [73,54,71,76,79,30,77,

---

* Corresponding author at: Department of Biochemistry, Faculty of Biological Sciences & Natural Science Unit, School of General Studies, University of Nigeria, Nsukka, Enugu State 410001, Nigeria.
** Corresponding author at: Department of Microbiology, Faculty of Biological Sciences & Natural Science Unit, School of General Studies, University of Nigeria, Nsukka, Enugu State 410001, Nigeria.
E-mail addresses: emmanuel.okeke@unn.edu.ng (E.S. Okeke), chidiebele.nwankwo@unn.edu.ng (C.E. Nwankwo).

https://doi.org/10.1016/j.toxrep.2024.03.012
Received 16 November 2023; Received in revised form 2 March 2024; Accepted 27 March 2024

78,53,67] derivatives); agrochemicals/chemical ripening [63,66,80,28,3,65,19,75] agents, heavy metals, [8] phthalates; antibiotics, pharmaceuticals and personal care [83,82,68,64,59,60] products, have been found to contaminate the food chains causing varieties of human and ecotoxicological harms. Per- and polyfluoroalkyl substances (PFAS) are synthetic chemicals that have been widely used in various consumer and industrial products such as non-stick surface repellents, textiles, cosmetics, papers, and firefighting foams since the 1950 s due to their unique ability to repel grease, dirt, and water [38]. Due to their chemical properties and applications, PFAS have a higher tendency to bioaccumulate and resist biodegradation, leading to significant consequences including environmental contamination and subsequent pollution of food sources [113]. There is a significant body of evidence that shows the harmful effects of PFAS on both wildlife and humans. Due to health, environmental, and regulatory concerns, preventing accidental contamination of food and food packaging has become the major focus. Scientists, researchers, and public health professionals have taken a leading role in assessing the risk of PFAS in food, with the goal of increasing global awareness of the potential consequences of consumer exposure and identifying gaps in knowledge. PFAS are known to be persistent, bio-accumulative, and potentially hazardous chemicals found in various environmental compartments. Their ubiquitous nature pose a serious threat to human health.

Ingestion of contaminated water, crops and livestock exposed to PFAS remain an important route of human exposure to PFAS [88]. Several studies show that food can get contaminated via soil and water used in growing the food, the accumulation of PFAS in animals as well as other food packaging materials and/or processing equipment/machine which contain PFAS [37]. Furthermore, seafood can absorb PFAS from their environment and dietary sources since they inhabit an aquatic ecosystem [57]. A 2018 report from the European Food Safety Authority (EFSA) has shown that egg, meat, milk seafood, drinking water, and other dairy products remain the most significant contributors to human diet [97]. Surveys of food samples from local supermarkets, including meats, fast food items, and seafood, in Canada and Sweden have reported the occurrence of PFAS in the commercial food supply [108] [34]. The highest concentrations of PFAS were detected in food samples collected (shellfish and fish) from the local supermarkets in Spain (Catalonia) in 2006 and 2008 [18]. Fourteen PFAS were detected in all 62 food samples from a retail shop in Dutch Netherlands in 2009, with lean fish, fatty fish, beef, and crustaceans having the highest detected concentration [61]. Some studies have analyzed the potential PFAS contamination in foods consumed in the US including wild-caught fish [29], and some other products from garden [95]. Recently, PFAS was detected in 15 out of 37 shellfish and finfish samples purchased in various locations in the United States, with freshwater fish from the Midwest having the highest concentration of PFAS (21.6 ng/g) [91]. Further assessment by Food Drug Administration (FDA) shows the presence of PFAS in 179 food samples purchased in a grocery store in the United State [36].

While many studies have extensively evaluated the toxicities of perfluorooctane sulfonic acid (PFOS) perfluorooctanoic acid (PFOA), there is little to no information on the environmental fate or toxicity of many other PFAS. As a result of limited information and the possible environmental impact of these group of chemicals, the National Institute of Health's National Toxicology Program (NTP) and the United State Environmental Protection Agency (USEPA) collaborated on conducting toxicity testing of PFAS to promote human health assessments of PFAS [85]. Table 1 reports the most diffused Per- and polyfluoroalkyl substances including their short-chain and long-chain differences. It's worth noting that while short-chain PFAS are generally considered less harmful than their long-chain counterparts, they are still chemicals of concern due to their persistence in the environment and potential health effects [89].

PFAS human exposure routes include food, non-stick cookware, fast food wrappers, grease-resistant paper, popcorn bags, and other FCMs [105]. Given the potential health risks and migration issues associated with PFAS in FCMs, it is crucial to develop analytical methods that can accurately and effectively quantify diverse PFAS in various food matrices. Over the years, several advanced and sensitive methods have been developed for the analysis of PFAS in different food matrices. In this review, we have extensively discussed the migration of PFAS from food packaging materials into food and provided evidence of PFAS occurrence in various food matrices and FCMs. We also reviewed recent analytical techniques for detecting and quantifying PFAS in food matrices and FCMs, along with associated challenges. Additionally, we discussed human exposure pathways to PFAS and the potential health impacts of exposure. Our aim was to add to the body of knowledge, providing ample information to consumers and public health researchers on the potentially toxic effects of this chemical upon exposure. Finally, we highlighted future prospects for reducing potential hazardous effects and food contamination.

Table 1
Most diffused per- and polyfluoroalkyl substances, including their short-chain and long-chain differences.

PFAS type	Carbon chain length	Characteristics
Perfluoroalkyl Substances (PFOS and PFOA)	Long-Chain	Highly persistent in the environment, bioaccumulative, and toxic. Used in industrial and consumer products. Banned or phased out in many countries.
Perfluoroalkyl Substances (PFHxS, PFNA, PFDA)	Long-Chain	Less persistent in the environment and less toxic than.
Polyfluoroalkyl Substances (GenX, PFBS)	Short-Chain	Similar to short-chain PFAS in terms of lower persistence and toxicity, but little is known about their environmental behavior and potential health effects. Used as alternatives to long-chain PFAS.
Emerging PFAS (PFPeA, PFDoA)	Varies	These are newer, lesser-known PFAS that are being studied for their environmental behavior and potential health effects. They may have short or long carbon chain lengths. Little is known about their use and exposure levels.

The main novelties of this work are related to a systematic literature review and analysis (see the next section) which allowed us to highlight emerging trends related to reducing or eliminating the use of PFAS in food packaging materials and increasing regulatory constraints on PFAS in the food industry. In addition, great attention is also devoted to the recent emerging regulatory issues. These findings highlight a growing awareness of the potential risks associated with PFAS exposure through food and the need for more stringent regulations to protect public health. Additionally, our study emphasizes the importance of continued research on the environmental distribution, occurrence, and sources of PFAS in the food system to better understand the scope and impact of this issue.

2. Study design

The objective of this review was to comprehensively examine the relevant literature on PFAS and food, in order to provide a summary and analysis of the current state of research and identify any current or developing research areas. To conduct a structured and comprehensive analysis of the literature, we utilized SCOPUS to gather data using the search terms (PFAS) AND (food) in the title, abstract, or relevant keywords of published articles. This literature search was carried on April 9, 2023, and the number of resulting publications was 569.

To perform an efficient bibliometric analysis, we utilized the VOSViewer software (https://www.vosviewer.com/), which allowed us to create a bibliometric map that graphically represents the co-occurrence network of abstracts and title text. This mapping technique allows users to visualize the relationships between different papers, authors, and research areas, providing insights into the structure and trends in the literature on PFAS and food.

The map generated by VOSViewer offer a 2D visualization of the research field, where closely related terms are located in close proximity to one another. This technique enables us to identify the most frequently used bibliographic terms and focus on the predominant thematic flow. The analysis produced a total of 14,903 terms, and by considering only those with a minimum occurrence of 10, we identified 5 distinct clusters. These clusters represent related research areas within the broader field of PFAS and food; allowing for a more targeted exploration of specific topics and subfields. Fig. 1 shows the map of the frequently used terms co-occurrence network. They were grouped into 5 clusters, represented by different colours.

The size of the circles in the image corresponds to the frequency of occurrence of the terms in the text of the papers. The red cluster (cluster 1) is primarily focused on the occurrence and environmental distribution of PFAS, with key terms including accumulation, organism, and ecosystems. This cluster contains the highest number of recurring terms (80 items). Cluster 2 (represented by green bubbles) is focused on population exposure, with key terms including exposure, plasma, women, and pregnancy. Cluster 3 (represented by blue bubbles) is dedicated to the sources of PFAS exposure, with terms such as ingestion and food packaging. Cluster 4 (represented by yellow balls) deals with the symptoms of PFAS ingestion. Finally, cluster 5 (represented by violet bubbles) includes a list of single contaminants. The proximity between the nodes indicates that there is a significant overlap between the terms used in both clusters. This explains why cluster 5 is located in the middle of clusters 1 and 2, while cluster 4 appears to be separated from the others. Based on the bibliographic cluster analysis, this review paper was conceived in different sections. The list of the most common PFAS (based on cluster 5 results) is reported in the introductive part. Section 3 discusses the PFAS migration into the food (mainly considering cluster 3 results). Section 4 considers the analytic techniques able to detect PFAS. Section 5 is devoted to dietary exposure, based on cluster 1 items. Section 6 describes the health impact of PFAS (based on clusters 2 and 4). The last review part considered the possibilities to reduce human exposure to PFAS. Finally, future perspectives were considered.

3. PFAS migration into food from food packaging/contact materials

Food contact materials (FCMs) could introduce harmful chemical substances into food via a migration process. PFAS have been found in several paperboards and food wrappers based on total fluorine measurement as a PFAS surrogate [93]. Migration is a process that cannot be prevented, and it is influenced by a variety of variables that follow Fick's diffusion principles. It depends on 1) the ability of the material to release PFAS, 2) the conditions of contact with food, such as temperature and length of exposure, 3) the qualities of the material in contact with food, such as thickness, initial concentration, and diffusion coefficient, and 4) the interaction between the material and the compound, expressed as the coefficient of distribution between the material and the food [96].

Exposure routes during processing and packaging mirror contemporary PFAS production and consumption. Fast food wrappers and other grease- and water-resistant packaging contain PFAS that can infiltrate into food and increase exposure via diet. The majority of PFAS now utilized in food packaging are short-chain types and fluorotelomers-based derivatives. Moreover, the migration is influenced by the concentration, mass fractions, type, and length of the PFAS chain as well as the type of food, even if there is only a brief period of interaction between the material and the food. The chain length of PFAS can affect their bioaccumulation potential and toxicity. Longer-chain PFAS, such as perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA), are more persistent and have a higher bioaccumulation potential than shorter-chain PFAS. This means that longer-chain PFAS can accumulate in the food chain more readily and have a greater potential for adverse health effects in humans. Temperature and time of contact

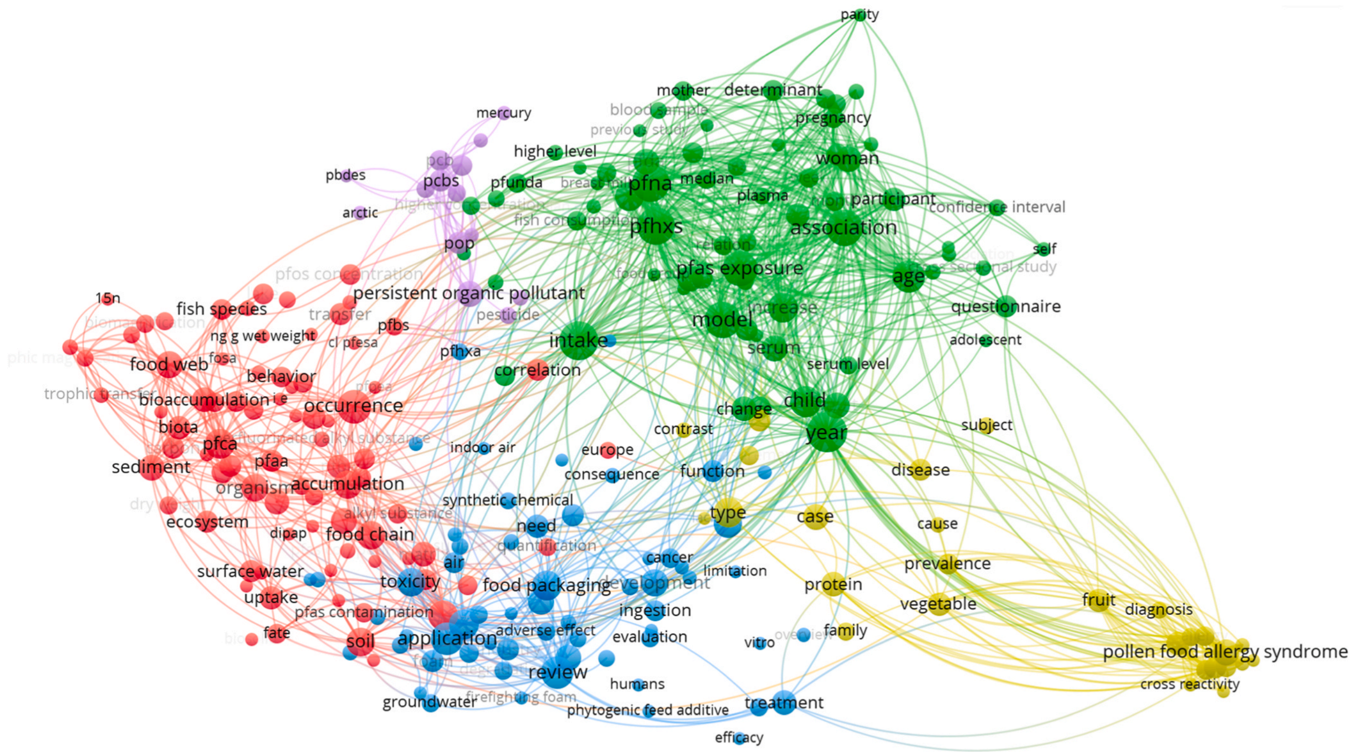

Fig. 1. Bibliographic analysis map of VOSviewer obtained by using the Scopus database, representing the co-occurrence network of the selected papers' keywords (PFAS and food). The data was updated on April 9, 2023.

can also influence the migration of PFAS from food packaging materials into food [93]. Higher temperatures can accelerate the migration of PFAS, especially from non-stick cookware and fast-food packaging, into the food. Longer contact times with food also increase the potential for migration of PFAS into the food.

The specific effects of these factors on food contamination can vary depending on the type of food and packaging material involved. For example, a study found that cooking eggs on a non-stick pan at high temperatures resulted in higher levels of PFAS migration into the eggs compared to cooking them on a stainless-steel pan. Similarly, a study reported that fast food packaging materials containing PFAS can lead to contamination of the food, especially when the food is hot and greasy [99].

Depending on whether PFAS is absorbed into the material or is only present on the material's surface, the first stage is the release of PFAS from the material's surface. The surface must be wet in order to dissolve the bonds that hold the substance to the surface and allow the chemicals to be released [109,117]. The second phase of PFAS migration occurs when the chemicals dissolve in food.

Because PFAS are environmental contaminants, it can be challenging to detect them in food as they may be present in the product before it is processed or packaged. Since they are easier analytical matrices than food, it is advised to utilize food simulants for these migration tests [25]. Additionally, it is important to ensure that the material the laboratory utilized was free from microbial contamination. In some investigations, a paper filter free of Teflon is utilized to substitute [11,10].

The following criteria were used for migration tests: For instance, since it is anticipated to attain high temperatures during food preparation, the migration circumstances employed in the case of a dish containing food to be heated in a microwave were 70 °C for 2 h [40]. For samples that cannot hold liquids, like baking paper, a portion of the sample is placed within the lid of a stainless steel cylinder, which is then sealed with a simulant for solid meals, like Tenax®, and placed in the oven at the right temperature and timing [11,10]. Prior to applying the simulant and exposing the samples to the proper temperature for the duration required for migration to occur [40], square cuts of the samples, such as muffin wrappers, pizza boxes, and hot beverage cups, are formed of them. This is in accordance with Commission Regulation (EU) No 10/2011 [24].

3.1. *Factor affecting PFAS migration in food*

3.1.1. *Moisture content*

The movement of PFAS into food is influenced by the amount of moisture in the food. PFAS are known to be hydrophobic, which means they repel water and are attracted to fats and oils. This can cause them to accumulate in fatty tissues of animals and also migrate from food packaging materials into fatty foods. In their study, Fengler et al. [31] investigated the migration of two samples of muffin masses. It was noted that the FTOH readings were lower for the sample with a higher moisture content than they were for the muffin with a lower moisture content. According to the authors, the FTOH evaporates, lowering its concentration in the food, which accounts for this variation [31].

3.1.2. *Fat content*

PFAS are most frequently detected in foods high in protein, including liver, game meat, farm animals, and fish because they can more easily bind to protein [26]. However, in migration tests, the fat level has a greater impact than the protein amount since these ingredients are employed to strengthen the material's resistance to lipids and are frequently found in the packaging of fast food and ultra-processed items. In order to demonstrate that PFAS do not migrate uniformly to all types of food, Choi et al. [11,10] examined a total of 312 samples, including pans, bakeware, electric rice cookers, grills, and baking papers. PFODA and PFNA, which are the analytes most often found in n-heptane and 50 % ethanol, respectively, moved in this case with the largest proportions. PFODA had a concentration of 3.05 $\mu g\ L^{-1}$ in the n-heptane simulant while PFNA had a concentration of 2.12 $\mu g\ L^{-1}$ in the simulant. These findings suggest that alcoholic beverages and fatty foods are the two dietary sources where PFC migration is most likely to occur [11,10]. In their investigation of the migration of perfluorinated compounds from paper bags to Tenax® and lyophilized milk, Elizalde et al. [20] revealed that migration of PFHxA, PFHpA, PFOA, PFNA, PFDA, PFTrDA, and PFTeDA was higher in whole milk than in low-fat milk. Low-fat milk had 50 % less fat than whole milk despite the fact that both types of milk were freeze-dried [20].

When compared to fatty diets that are not emulsified, emulsified foods have higher migration levels. In their study on the migration of PFAS in emulsified foods, Begley et al. [5] reported that the migration rate was up to 50 times greater in emulsified foods like butter than it was in non-emulsified fats like oil. The migration of PFAS at 100 °C is predicted to rise when the amount of ethanol in relation to water increases from 10 % to 30 %, as was the case in the migration employing food simulants.

3.1.3. *pH*

PFAS are known to be more stable in acidic environments, meaning that they can be more easily released into acidic foods. In contrast, in more basic environments, such as in some types of vegetables, PFAS are less likely to migrate into the food.

Studies have shown that PFAS migration into food can be influenced by the pH of the food [1]. PFAS migration into food was higher when the food was acidic (pH 4.0) compared to when it was neutral (pH 7.0). Acidic beverages, such as orange juice, was found to have higher levels of PFAS contamination compared to other beverages with a more neutral pH.

3.1.4. *Salt content*

The WHO estimates that between 10 and 12 g of salt are ingested daily. This consists of both precooked meals and salt added during cooking and processing. It is therefore interesting to know how salt content affects perfluoroalkylated compound migration in food [114].

Research has shown that the transmission of PFAS is reportedly accelerated by sodium chloride [1]. This is because NaCl can break down the repulsive forces between PFAS and surfaces, making it easier for PFAS to migrate or transfer onto food. When PFOS and PFOA migration from a non-stick utensil to food was compared between salt-added and salt-free foods, it was found that the migration was higher in salt-added foods than in salt-free foods.

4. Analytical techniques for determination PFAS in food matrices and food-contact materials

Humans get exposed to PFAS in a number of ways, but one of the main entry routes is through food consumption. As a result, PFAS detected in packaging materials that come into contact with food directly have received a lot of attention in recent years. PFAS utilized in food contact boards and paper have been shown to be persistent, bioaccumulate and very hazardous. Analytical techniques are required to identify the sources of PFAS exposure via board and paper, as well as to evaluate their impure constituents and degradation products. As a result, additional fluorinated compounds may emerge, and there is no universal method for the analysis and identification of all PFAS [110]. Because polyfluorinated surfactants are complex mixtures, they pose an analytical risk and call for high-performance analytical methods to identify all the potential constituents [109]. The total fluorine in samples can be determined using a number of non-specific methods including some spectroscopic methods like nuclear magnetic resonance (NMR), and sliding spark spectroscopy [94]. Additionally, instrumental neutron activation analysis is a very good technique for the determination of total fluorine [98]. It is important to identify PFAS since fluorine can be found in other fluorinated chemicals or as inorganic fluorine. Since they are present in low concentrations and these samples typically comprise a variety of other PFAS, it is challenging to identify these types of substances [32]. Liquid chromatography coupled to a mass spectrometry detector (LC-MS or UPLC-MS) as well as tandem mass spectrometry has also been used to determine the content of PFAS in food-contact materials [11,10,21].

Liquid chromatography coupled to triple quadrupole mass spectrometry (LC-QqQ) and liquid chromatography coupled to quadrupole time-of-flight mass spectrometry (LC-QTOF) was recently developed, for the detection of low levels of PFAS in food packaging materials [56]. Fluorine was detected in paper samples designed for food packing at a concentration above 16 nmol/cm^2 [92]. Also, liquid chromatography coupled to mass spectrometry (LC-MS) was developed by some scientists in Sweden and Denmark for the determination of PFAA and some PFOS derivatives and other total organic fluorine [109]. Thirteen out of the 35 samples analyzed including muffin packaging, popcorn bags, fast-food packaging, and baking dishes contained PFAS [39]. Table 2 outlines some techniques for the extraction and analysis of PFAS in food matrices and FCMs.

Fresh paper fiber does not naturally contain PFAS. To stop packaging from absorbing water and fat, they are frequently placed into a layer that is applied to paper and board. They may also be added throughout the recycling process to the finished product. Depending on the intended type of study, a variety of different analytical techniques are employed for the detection and quantification of PFAS in food packaging materials. However, liquid chromatography combined with triple quadrupole mass spectrometry (LC-MS/MS) is the technology that is both the most sensitive and selective. PFAS extraction from paper and board matrices was recently evaluated by scientists at the Institute of Analytical Chemistry and Food Chemistry at the Graz University of Technology in Austria, using accelerated solvent extraction (ASE), followed by quantification using LC-MS/MS. They analyzed 24 common PFAS substances found in paper FCMs. Specifically, 5 L of the prepared solution was injected into a Shimadzu LCMS-8050 system for PFAS analysis. A Restek Raptor C18 column was used to chromatographically separate the analytes. The Restek Delay column, which was positioned between the mixer and the autoinjector, was used to separate any PFAS that might accidentally leak out of the instrument upstream of the injector. The technology for specifically identifying and precisely quantifying PFAS in food packaging was successfully developed by the Graz researchers. Apparently, the recovery values were ranged between 84–94 %, and the detection limit was between 0.1 and 0.5 ng/g. Consequently, they came to the conclusion that the highly regarded Shimadzu LCMS-8050 is well suited for high-throughput multi-component analysis due to its combination of high sensitivity and exceptional speed parameters, allowing for accurate measurement of PFAS concentration ranges up to 0.01 pg/L. Therefore, it is advantageous to use the LCMS-8050 as a key component of a quick and effective approach to monitor and quantify PFAS in paper-based food packaging materials.

5. Dietary exposure pathways/routes to PFAS

The main human exposure routes to PFAS involve various dietary routes, including

1. Consuming food that has been contaminated with PFAS, either through direct contact with PFAS-containing materials during production, processing, packaging, and storage, or through contamination of soil, water, and air used in food production.
2. Consuming food from animals that have been exposed to PFAS, either through contaminated feed or environmental exposure.
3. Consuming seafood that has been contaminated with PFAS, as these chemicals can accumulate in the aquatic food chain.
4. Using cookware, food packaging, or other FCMs that contain PFAS, which can leach into food during cooking or storage.
5. Ingesting PFAS-contaminated water used for cooking, drinking, or food processing.

Over the past 70 years, several industries have utilized PFAS, a class of synthetic organofluoride compounds that persist in the environment. The reproductive, endocrine, and immune systems of humans may be at risk from exposure to some PFAS, particularly long-chain types, according to toxicological research. Here, a theoretical model of PFAS exposure that explains the sources, the mechanisms of transport, and the exposure routes to humans will be discussed. Point sources and non-point sources are the two main sources that contribute to human PFAS exposure. Industrial operations, such as fire training/response locations, are linked to primary point sources, while non-point sources may include food items, food packaging, and drinking water. Depending on the chemical components of the PFAS, transport pathways can include runoff to surface water, long-range atmospheric deposition, and migration to groundwater. All of these processes could contaminate

Table 2
Techniques for extraction and analysis of PFAS in food and food contact materials.

Food/food contact material	Compound	Extraction method	LOD/LOQ	References
Popcorn bag	PFHxA, PFTeDA, PFBA, PFPeA, PFHpA, PFDA, PFNA, PFDoDA, PFOA, PFUnDA, PFTrDA, PFPeDA, PFHxDA etc.	Focused ultrasonic solid-liquid extraction	0.6–2.2 ng/g	[121]
Plastic and cardboard materials	PFHxS, PFBA, PFBS, PFHxA, PFPeA, PFOS, PFOA, PFDA, PFNA, PFHpA, PFOPA, PFOSA, PFHxPA, PFDPA etc.,	Ultrasonic probe-assisted extraction	0.6–2.2 ng/L	[120]
Food packaging materials	PFDS, PFPeA, PFTrDA, PFHpA, PFBA, PFNA, PFOA, PFHxA, PFDA, PFTeDA, PFUnDA, PFBS, PFOS, PFDoA, PFHxS, PFODA, PFHxDA	PLE	5–30 ng/g	[119]
Breast milk	PFPeA, PFHxA, PFHpA, PFOA, PFNA, PFUnDA, PFTrDA, PFDA, PFHS, PFDoDA, PFTeDA, PFOcDA, PFHxDA, PFBS, PFDS, PFOS	MTBE	0.025–0.01 ng/ml	[48]
Fish liver and muscle	PFPeA, PFOPA, PFHpA, PFBA, PFHxA, PFNA, PFDA, PFHxS, PFOSA, PFBS, PFHxPA, PFOS, PFDPA	Focused ultrasonic solid-liquid extraction	1.4–8 ng/g	[119]
Fish liver	HFPO-DA	IPE (TBAS + MTBE)	0.05–0.10 ng/g ww	[112]
Vegetables and fish	PFBA, PFHxA, PFHxPA PFHpA, PFOPA, PFPeA, PFHxS, PFBS, PFNA	Focused ultrasound solid-liquid extraction	0.3–12.4 ng/g	[118]
Fish tissue	AFFF	MeOH + NH$_4$OH	0.027–0.54 ng/g ww	[50]
Fish	PFOS, PFOA	SPE	5.4–17.2 ng/g	[102]
Fish homogenates	FBSA	SLE (ACN + FA)	0.010 ng/g ww	[12]
Fish muscle	PFPCPeS, PFECHS	MeOH + KOH	0.22–0.39 ng/g dw	[13]

Key: Perfluorononanoic acid (PFNA); perfluorooctanoic acid (PFOA); perfluorooctanesulphonate (PFOS); perfluorobutane sulphonic acid (PFBS); perfluorononane sulphonic acid (PFNS); perfluoro alkane sulfonamido ethanols (PFASEs); perfluorooctanoic acid (PFHxA) agricultural produce and, in the end, expose humans to PFAS.

According to European data, drinking water is the single most significant source of PFAS exposure to humans, second only to point-source contamination. Lakes, groundwater, and rivers are drinking water sources that may be contaminated with PFAS leaching from industrial sources. In particular, due to high solubilty in water, PFAS have been detected in various water sources close to high-probability point sources, including fire-fighting and manufacturing facilities. Our knowledge of PFAS water pollution has significantly increased because of state-wide and national surveys conducted between 1999 and 2017. These survey findings suggest that the PFAS concentrations in some drinking water surpass the EPA's 2016 health advisory guideline of 70 ng/L for PFOS and PFOA alone or both, possibly exposing about 6 million US citizens [105]. The EPA's advisory limits for PFOA and PFOS were significantly revised in 2022. The new advisory limits set by the EPA are much stricter, with revised Health Advisory Levels of 0.004 ng/L for PFOA and 0.02 ng/L for PFOS [22]. These updated guidelines reflect the EPA's commitment to protecting public health from the potential risks associated with exposure to these substances in drinking water. It is important to note that these health advisories are non-regulatory and non-enforceable but serve as crucial health protective information for regulators and the public [22]. These stricter guidelines reflect the EPA's commitment to protecting public health from the risks associated with exposure to PFAS in drinking water [22].

Additionally, there may be a high risk of exposure to PFAS-contaminated sewage sludge (biosolids) and recycled water from wastewater treatment facilities, which are frequently utilized in agriculture [105]. However, to understand the proportional contribution of different PFAS sources to the human diet, extensive research is needed. Due to its distinct functional characteristics, PFAS are used in a variety of consumer items throughout the world. Grease-resistant paper, non-stick cookware, wrappers of fast food, retail packaging etc., are only a few of the possible exposure routes for PFAS. In accordance with FDA regulations, the use of long-chain PFAS was voluntarily stopped by manufacturers in the USA and is not deliberately used in food packaging. Short-chain PFAS and fluorinated acrylate polymers are nevertheless allowed to be used in packaging and other commercial applications. Occupational exposure is another important PFAS exposure pathway. Individuals who work in industries where PFAS is produced or where it's used in or incooperated in food packaging materials are also at risk. The bioaccumulation potential of PFAS has been demonstrated, and it increases with increasing chain length. Certain PFAS compounds have been demonstrated to have an influence on human health through altered thyroid and renal function, immunosuppression, and harmful effects on reproduction and development. Chronic conditions linked to perfluorooctane sulfonate (PFOA) have been reported including kidney and testicular malignancies, excessive cholesterol and ulcerative colitis [105].

To a greater extent, bioaccumulation at the source and exposure through processing and packaging are the two major pathways through that PFAS gain entry into food (Fig. 2). Long-term PFAS uses are typically reflected by bioaccumulation-related pathways, which can also involve biosolids, which are industrial ashes and sludges that contain nutrients that can improve agricultural and soil productivity. The PFAS in biosolids has the potential to leach into groundwater and contaminate drinking water [44,95]. They can potentially be absorbed by crops, which exposes humans to them through food [100].

PFAS can accumulate in various plants and animals that are commonly eaten as food, with different mechanisms and patterns of accumulation. In plants, PFAS can accumulate through uptake from contaminated soil and water, as well as through atmospheric deposition. Once taken up by the plant, PFAS can be translocated to other parts of the plant, including edible parts, such as leaves, fruits, and seeds. The accumulation of PFAS in plants is influenced by factors such as plant species, soil type, pH, and moisture content. In animals, PFAS can accumulate through dietary intake, as well as through inhalation or dermal exposure to contaminated water, soil, or air. PFAS can accumulate in various animal tissues, including muscle, liver, and adipose tissue. Certain long-chain PFAS, especially PFOS, have a considerable potential to accumulate in beef and fish when compared to short-chain PFAS accumulation in crops [55]. Additionally, unlike other persistent chemicals, in muscle, kidney, and liver tissue, PFAS tend to segregate to

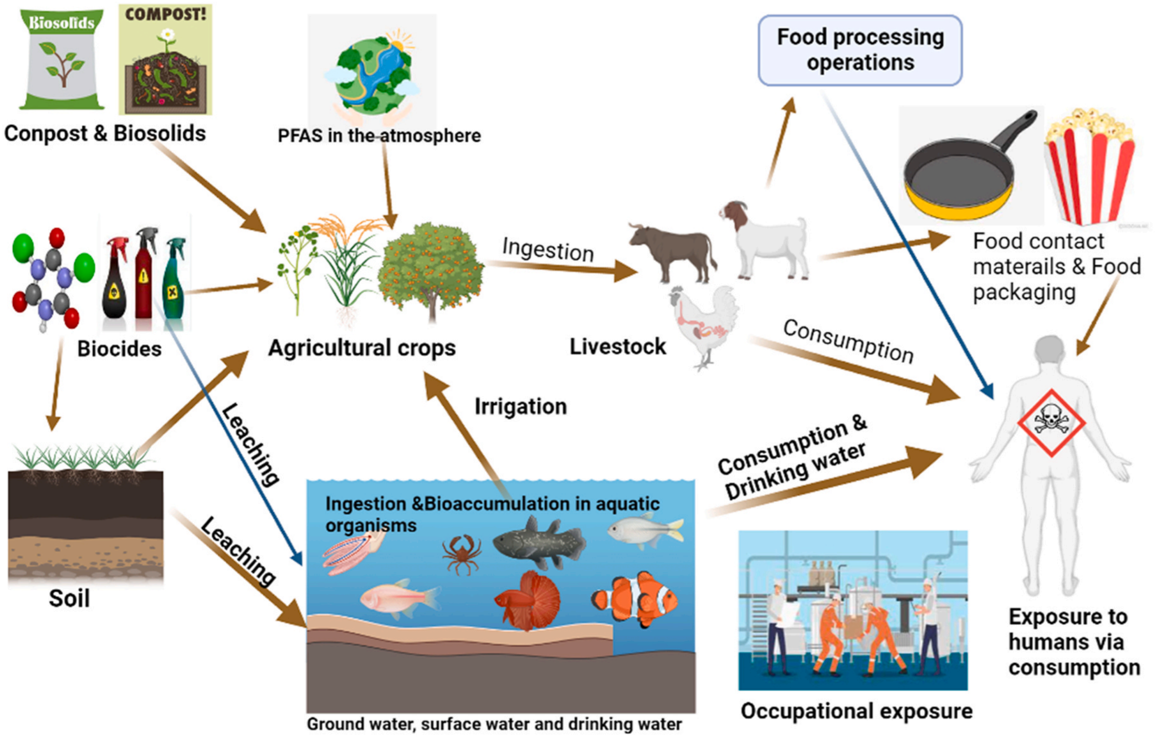

Fig. 2. Potential routes for PFAS entry into the food chain and human exposure.

proteins rather than lipids [45]. The accumulation of PFAS in animals is influenced by factors such as animal species, age, sex, and diet.

The patterns of accumulation of PFAS in different plants and animals can also vary depending on the specific types of PFAS present and their physicochemical properties. For example, long-chain PFAS tend to accumulate more in animal tissues than short-chain PFAS, while certain types of PFAS, such as PFOS, have been found to accumulate more in certain types of fish, such as tuna and salmon.

In 2016, the National Toxicology Program (NTP) conducted a comprehensive evaluation of human, animal, and laboratory studies investigating the immunotoxic effects of PFOA and PFOS [62]. The outcome of this thorough assessment indicated that both PFOA and PFOS are deemed to pose potential immune-related risks to humans. The review found compelling evidence linking both substances to the suppression of the antibody response. Additionally, there was less robust evidence suggesting that PFOA could lead to reduced resistance to infectious diseases, heightened hypersensitivity-related outcomes, and increased incidence of autoimmune diseases. Similarly, PFOS was associated with the suppression of natural killer cell activity. Similarly, perfluoroalkyl substances have demonstrated the ability to impact thyroid hormone levels in rats, and studies have identified correlations between serum perfluoroalkyl concentrations and thyroid hormone levels in human epidemiological research. While limited data exist on the mechanisms behind thyroid hormone disruption by perfluoroalkyls, available evidence suggests that these substances may affect thyroid function by binding to the thyroid hormone receptor or modifying the expression of genes involved in thyroid function and regulation. Research has shown that various perfluoroalkyls can bind to the human thyroid hormone receptor in cultured GH2 cancer cells and through molecular docking experiments [90]. In these laboratory tests, all 16 compounds tested displayed lower affinity for the receptor compared to T3. Among these compounds, PFOS exhibited the most potent agonist activity [90]. Limited results from laboratory studies indicate that perfluoroalkyls could potentially interact with estrogen and androgen receptors. PFOA, PFOS, PFHxS, PFNA, and PFDA were identified as androgen receptor antagonists, while PFOA, PFOS, and PFHxS activated the estrogen receptor [46]. Analyzed gene expression data from the livers of wild-type and PPARα-null mice exposed to PFOA, PFOS, PFHxS, and PFNA for 7 days showed similarities to gene expression changes caused by known ERα agonists, suggesting perfluoroalkyl effects in the liver through ER activation. Oral doses of up to 1 $mgkg^{-1}$ of PFOA did not cause any changes in uterine weight, ER-dependent gene expression, or reproductive organ morphology in immature CD-1 mice during uterotrophic assays [116]. This indicates that PFOA is either inactive in living organisms or has very low estrogenic strength.

It is important to note that PFAS exposure can also occur through non-dietary routes, such as inhalation of contaminated air, dust, or fumes, and through skin contact with PFAS-containing products, as better discussed in the next section.

6. Human health impact of exposure to PFAS

Humans get exposed to PFAS primarily through three ways including ingestion (e.g. drinking, eating, or accidentally swallowing foods and beverages contaminated with PFAS), inhalation (e.g. inhaling dust, soil, or air contaminated with PFAS), and/or physical contact (e.g. when applying cosmetics and personal care products contaminated with PFAS) [15,103,107] as seen in Fig. 3**A**. Amongst the three, dietary intake when eating or drinking accounts for the most frequent exposure mechanism [105]. It is also important to note that the exposure levels will differ depending on different factors like geography (e.g. subpopulations may be more at risk than the general public), occupation (e.g. industrial workers involved in production and processing PFAS or PFAS-producing products may be more at risk), age and status (e.g.

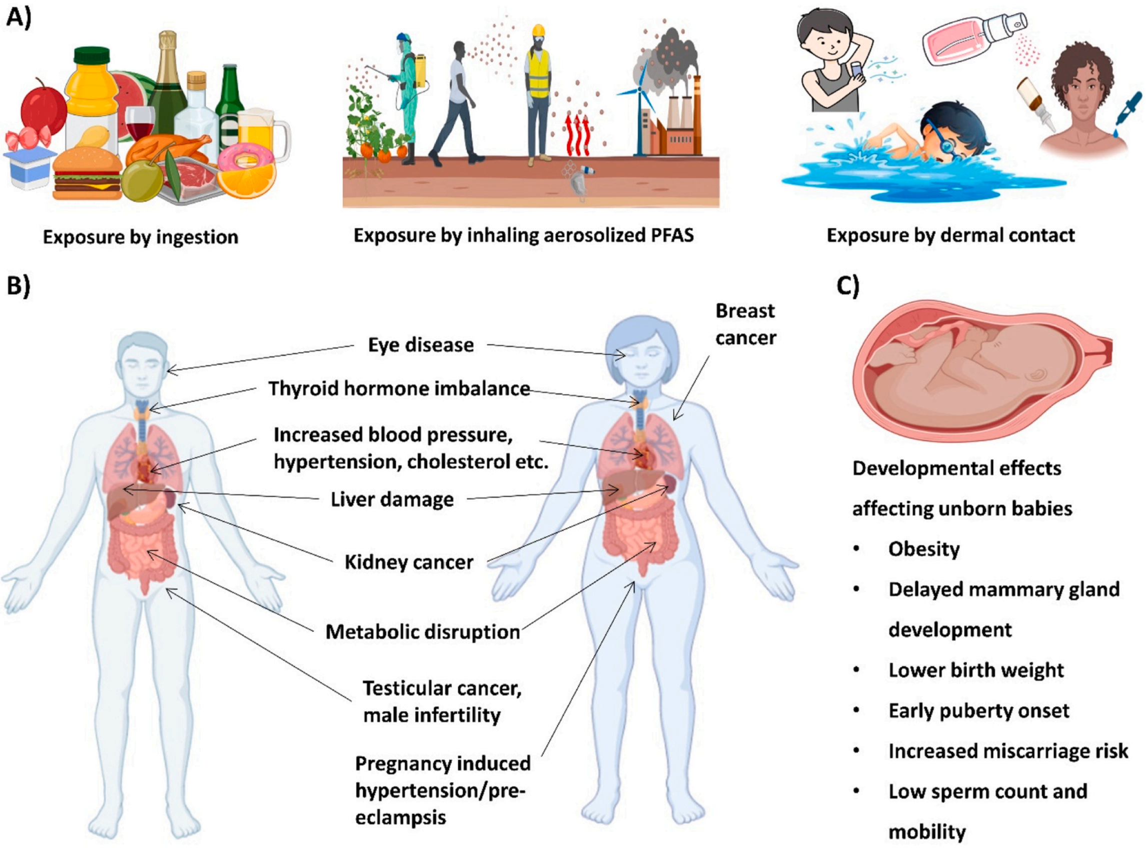

Fig. 3. Human exposure routes to PFAS (A) and examples of associated diseases caused to humans (B) and unborn fetus (C), as a result of the exposure.

growing children may be more sensitive to PFAS and pregnant or lactating mothers tend to drink more water than the average person increase exposure risk to themselves and the fetus) etc. [103].

Once exposed, PFAS may continue to accumulate in various parts of the human body. The health effects associated with this exposure can only be determined if these levels become toxic [14]. Due to the ubiquity of PFAS in human blood, it is the most frequently used sample matrix to screen for PFAS toxicity in human serum internationally. Several studies have reviewed the levels of PFAS in human blood and the results indicated that PFAS levels in occupationally/otherwise exposed individuals were higher than those of the general population (people with no known exposure point). For example, Jian et.al [43] reviewed 87 articles and found the range of PFAS in human blood to be between 0.01 and 10, 400 ng/ml (with fishermen in China accounting for the highest concentrations). Silva et.al [14] also reviewed several works of literature and observed that the level of PFAS in occupationally exposed individuals was 1–4 × higher in the order of magnitude compared to that of the general population. Also, Piekarski et al. [86] reviewed 35 articles to generalize that the global amounts of perfluoroalkyl acids (PFAAs) in adult serum of the general public were about 0.5–35.5 ng/ml, while that of the occupationally exposed individual ranged from 12.7 and 2190 ng/ml.

Current peer-reviewed studies have shown that exposure to PFAS can have several detrimental effects on human health as summarized in Fig. 3**B**. These studies have shown that PFAS can directly cause disease or weaken the immune system to increase pre-existing disease pathogenicity. The most commonly observed human health effects include; reproduction problems like decreased fertility or increased blood pressure in expectant mothers [33,106], increased risks of cancer development (e.g. kidney and testicular cancer) [104], hormonal imbalance [17, 47], increased cholesterol levels that can cause obesity [4], and elevated blood pressure and hypertension in highly exposed young adults [87]. With the continued spread of coronavirus disease 2019 (COVID-19), concerns have also been raised by the public if PFAS increases COVID-19 disease severity. In a study conducted in Shanxi and Shandong provinces [42], two regions heavily polluted by PFASs in China, a positive correlation between COVID-19 with PFAS perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) was observed in urine samples. The study concluded that elevated exposure to PFOS and PFOA, two of the most toxic and widely used compounds, was independently associated with increased risks of COVID-19 [42]. In support, three other studies have also shown that there is a higher mortality risk for COVID-19 in a population heavily exposed to PFAS [7,58], and perfluorobutanoic acid (PFBA) in plasma samples increased risk of a more severe course of COVID-19 [41]. With the growing range of evidence, concerned agencies in various governmental and non-governmental organizations should review the literature and come up with guidelines to protect the general public.

Besides causing disease and other health effects to adults, maternal, infant, and fetal exposure to PFAS have been documented globally [51]. PFAS have been detected in newborn serum, cord serum, maternal serum, and breast milk which is indicative of placental transfer of PFAS during pre- and postnatal care [103,122]. In a study, the exposure levels of PFAS followed in the order of maternal serum > cord serum > breast milk [122]. Also, breast milk has been found to account for 83–99 % of totally consumed PFAS by infants. However, based on the current scientific knowledge, benefits of breastfeeding outweigh exposure to PFAS from contaminated milk [111]. One need to consult a doctor to properly weigh the risks if concerned. Beyond maternal transfers, infants are at a higher risk of PFAS exposure because; they drink more water, eat more food, and breathe more air relative to their body weight compared to adults [115]. Babies fed formula may also experience increased daily exposure to PFAS, as the powders may be contaminated when mixed with water [6,52]; and young children put things in their mouth, cannot take care of their personal hygiene (e.g. hand washing), and crawl on floors which may expose them to PFAS in cleaning/household products, carpets, toys etc. As shown in Fig. 3**B**, this exposure may lead to number of health effects to the newborns such as obesity [35], lowered birth weight [9,101], early puberty onset [23,49], and many more. Lastly, it is important to note that the health effects linked to PFAS exposure are hard to classify for many reasons as: few PFAS compounds are studied despite the existence of thousands of PFAS all having distinct/varying toxicity levels; exposure to PFAS can vary per individual at different life stages; and PFAS usage and types change overtime proving difficult to assess a single PFAS exposure effect to human health. Despite these limitations, scientific evidence and continued surveillance still play critical roles in not only identifying the cause and effects of new and pre-existing PFAS but also protecting the public from health associated effects of PFAS.

7. Alternative materials to PFAS to reduce toxicity and human exposure

Efforts are being made to reduce or eliminate the use of PFAS in food packaging materials due to concerns about their potential health effects on humans and the environment. Many countries have already banned or restricted the use of certain types of PFAS in food packaging materials, such as PFOA and PFOS. For example, in the European Union (EU), certain types of PFAS in FCMs are restricted under the REACH regulation, and PFOA is banned in all FCMs since 2020. In February of 2023, authorities from Denmark, Germany, the Netherlands, Norway, and Sweden presented a proposal to the European Chemicals Agency with the aim of reducing PFAS emissions into the environment and improving the safety of products and processes for people. The European Chemicals Agency has released the specifics of the proposed restrictions for around 10,000 PFAS on their website (https://echa.europa.eu/home). A six-month consultation period commenced in March of 2023.

In the United States, the FDA has established voluntary phase-out agreements with industries to stop using certain types of PFAS in FCMs. In addition, some states, such as Maine and Washington, have passed laws that restrict or ban the use of PFAS in food packaging materials. Other countries, such as Canada and Japan, have also taken actions to limit the use of PFAS in FCMs. In Canada, the government has prohibited the use of PFAS in certain food packaging materials and has set limits on the amount of PFAS that can be present in drinking water. Japan has also introduced regulations that restrict the use of PFAS in food packaging materials, as well as in food containers and utensils.

In this frame, manufacturers are exploring alternative materials that can provide similar properties to PFAS but without the potential health and environmental risks. For example, some companies are using plant-based coatings that are biodegradable and compostable. Others are using coatings made from materials such as silicone, which do not contain PFAS and have been shown to be effective in repelling water and oil.

Some of these alternatives include:

1. **Plant-based coatings:** Some companies are developing plant-based coatings made from materials such as cellulose, starches, and proteins that can provide similar non-stick and water-repellent properties as PFAS.
2. **Silicone-based coatings:** Silicone-based coatings have been used as an alternative to PFAS in some food contact applications, such as baking paper and muffin cups. These coatings have good release properties and are considered safe for use in FCMs.
3. **Wax coatings:** Wax coatings, such as beeswax and carnauba wax, can provide water-resistant and grease-resistant properties and have been used as an alternative to PFAS in some food packaging applications.
4. **Fluoropolymer-free barrier coatings:** Some companies are developing barrier coatings that do not contain PFAS or other fluoropolymers. These coatings use other types of polymers, such as

polyethylene or polypropylene, to provide a barrier against moisture and grease.

5. **Natural antimicrobial coatings:** Natural antimicrobial coatings, such as those made from chitosan or other natural polymers, can provide protection against bacteria and other microorganisms in food packaging.

8. Research challenges and future perspectives

PFAS are synthetic chemicals, and new substances are continually being produced and added to the existing class. This poses a potential health risk, as the majority of these new PFAS are created as substitutes for the ones already in use. PFAS exposure can cause various health effects, including cancer, thyroid hormone disruption, immune system dysfunction, and developmental and reproductive harm. The main route of exposure is through contaminated food and water sources.

However, the toxicity and features of these alternate PFAS and their precursors are not fully understood, necessitating further research to develop effective treatment methods. Consequently, identifying, characterizing, and describing these new PFAS in the environment is challenging.

Human exposure to PFAS depends on various factors such as lifestyle and food consumption, leading to different pathways of exposure in various regions. Therefore, in-depth investigations into exposure pathways and related health hazards should be conducted in different global regions. To reduce PFAS impact, a long-term method for determining their sources and pathways is crucial.

The low concentrations at which PFAS frequently occur in the environment pose a significant challenge to their elimination, requiring the use of accurate and efficient sampling, analysis, and determination techniques. Gas and liquid chromatographic techniques are the most reliable methods for laboratory-scale analysis. However, the current methods for detecting, treating, and analyzing PFAS are inefficient and unsustainable, and there is a lack of knowledge and comprehension regarding their removal from the environment.

To ensure food safety, it is crucial to regulate the use of PFAS in food production and minimize their release into the environment. This requires stringent monitoring and testing of food items to detect any PFAS contamination. The food industry also has a responsibility to adopt sustainable practices that minimize the use of PFAS in food production and processing.

Overall, the use of PFAS in food production is a growing concern for public health officials globally. It is essential to prioritize food safety by regulating the use of PFAS and implementing sustainable practices that minimize their release into the environment. This will help to reduce the occurrence of foodborne illnesses and ensure that individuals have access to safe and healthy food supplies.

9. Conclusion

PFAS are a large class of compounds found in nature at very low concentrations. PFAS are present in every aspect of life, but because of the potential harm they could cause to humans, animals, and the environment, they are classified as emerging pollutants. The main difficulty in eliminating PFAS is that they frequently present in the environment at low concentrations, which necessitates the use of accurate and efficient sampling, analysis, and determination techniques. For laboratory-scale analysis, gas and liquid chromatographic techniques are regarded as the most reliable. These methods are also challenged by the ever emerging and increasing number of PFAS in the environment making calibration difficult. To better grasp the potential effects of these contaminants and comprehend thorough and practical solutions for their effective removal from the environment, more systematic and well-designed studies are required. The capacity to precisely assess pollutants is crucial for everything from human safety to the general security of our planet. Only then can the dangers be accurately evaluated and preventative measures taken. PFAS currently offer a risk that merits measurement, despite their numerous advantages.

Ethics declarations

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Funding

This article did not receive any form of funding. The graphical abstract was realised by using free flaticon icons.

CRediT authorship contribution statement

Onyekwere Joseph Okoro: Conceptualization, Data curation, Formal analysis, Writing – original draft. **Uttpal Anand:** Data curation, Formal analysis, Writing – original draft. **Raphael Nyaruaba:** Conceptualization, Writing – original draft, Writing – review & editing. **Chukwuebuka Gabriel Eze:** Conceptualization, Writing – original draft, Writing – review & editing. **CHIDIEBELE Emmanuel Ikechukwu NWANKWO:** Conceptualization, Writing – original draft, Writing – review & editing. **Elza Bontempi:** Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Emmanuel Sunday Okeke:** Conceptualization, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgements

Authors are thankful to their respective departments/institutes/universities for providing space and other necessary facilities, which helped draft this manuscript.

References

[1] M.M. AbulFadl, A.M. Sharaf, M.M. Mostafa, M.H. El-Saeid, Impact of household cooking on release of fluorinated compounds PFOA and PFOS from Tefal coated cookware to foods, World J. Adv. Res. Rev. 3 (2019) 024–030, https://doi.org/10.30574/wjarr.2019.3.2.0060.

[2] O.D. Akan, G.E. Udofia, E.S. Okeke, C.L. Mgbechidinma, C.O. Okoye, Y.A. B. Zoclanclounon, E.O. Atakpa, O.O. Adebanjo, Plastic waste: Status, degradation and microbial management options for Africa, Journal of Environmental Management 292 (2021) 112758, https://doi.org/10.1016/j.jenvman.2021.112758.

[3] E.G. Anaduaka, N. Orizu, O.R. Asomadu, L.A. Ezugwu, E.S. Okeke, T.P. C. Ezeorba, Widespread use of toxic agrochemicals and pesticides for agricultural products storage in Africa and developing countries: Possible panacea for ecotoxicology and health implications, Heliyon 9 (2023) e15173, https://doi.org/10.1016/j.heliyon.2023.e15173.

[4] M.E. Andersen, B. Hagenbuch, U. Apte, J.C. Corton, T. Fletcher, C. Lau, W. L. Roth, B. Staels, G.L. Vega, H.J. Clewell, M.P. Longnecker, Why is elevation of serum cholesterol associated with exposure to perfluoroalkyl substances (PFAS) in humans? A workshop report on potential mechanisms, Toxicology 459 (2021) 152845, https://doi.org/10.1016/J.TOX.2021.152845.

[5] T.H. Begley, K. White, P. Honigfort, M.L. Twaroski, R. Neches, R.A. Walker, Perfluorochemicals: potential sources of and migration from food packaging, Food Addit. Contam. 22 (2005) 1023–1031, https://doi.org/10.1080/02652030500183474.

[6] B.E. Blake, S.E. Fenton, Early life exposure to per- and polyfluoroalkyl substances (PFAS) and latent health outcomes: a review including the placenta as a target

tissue and possible driver of peri- and postnatal effects, Toxicology 443 (2020) 152565, https://doi.org/10.1016/J.TOX.2020.152565.

[7] D. Catelan, A. Biggeri, F. Russo, D. Gregori, G. Pitter, F. Da Re, T. Fletcher, C. Canova, Exposure to perfluoroalkyl substances and mortality for COVID-19: a spatial ecological analysis in the Veneto Region (Italy), Int. J. Environ. Res. Public Health 18 (2021) 1–12, https://doi.org/10.3390/IJERPH18052734.

[8] H. Chen, K. Chen, X. Qiu, H. Xu, G. Mao, T. Zhao, W. Feng, E.S. Okeke, X. Wu, L. Yang, The reproductive toxicity and potential mechanisms of combined exposure to dibutyl phthalate and diisobutyl phthalate in male zebrafish (Danio rerio), Chemosphere 258 (2020), https://doi.org/10.1016/j.chemosphere.2020.127238.

[9] L. Chen, C. Tong, X. Huo, J. Zhang, Y. Tian, Prenatal exposure to perfluoroalkyl and polyfluoroalkyl substances and birth outcomes: a longitudinal cohort with repeated measurements, Chemosphere 267 (2021) 128899, https://doi.org/10.1016/J.CHEMOSPHERE.2020.128899.

[10] H. Choi, I.A. Bae, J.C. Choi, S.J. Park, M.K. Kim, Perfluorinated compounds in food simulants after migration from fluorocarbon resin-coated frying pans, baking utensils, and non-stick baking papers on the Korean market, https://doi. Org. /10. 1080/19393210. 2018. 1499677 11 (2018) 264–272, https://doi.org/10.1080/19393210.2018.1499677.

[11] H. Choi, I.-A. Bae, J.C. Choi, S.-J. Park, M. Kim, Perfluorinated compounds in food simulants after migration from fluorocarbon resin-coated frying pans, baking utensils, and non-stick baking papers on the Korean market, Food Addit. Contam. Part B 11 (2018) 264–272, https://doi.org/10.1080/19393210.2018.1499677.

[12] S. Chu, R.J. Letcher, D.J. McGoldrick, S.M. Backus, A new fluorinated surfactant contaminant in biota: perfluorobutane sulfonamide in several fish species, Environ. Sci. Technol. 50 (2016) 669–675, https://doi.org/10.1021/ACS.EST.5B05058.

[13] Q. Cui, Y. Pan, H. Zhang, N. Sheng, J. Wang, Y. Guo, J. Dai, Occurrence and tissue distribution of novel perfluoroether carboxylic and sulfonic acids and legacy per/polyfluoroalkyl substances in black-spotted frog (Pelophylax nigromaculatus), Environ. Sci. Technol. 52 (2018) 982–990, https://doi.org/10.1021/ACS.EST.7B03662.

[14] A.O. De Silva, J.M. Armitage, T.A. Bruton, C. Dassuncao, W. Heiger-Bernays, X. C. Hu, A. Kärrman, B. Kelly, C. Ng, A. Robuck, M. Sun, T.F. Webster, E. M. Sunderland, PFAS exposure pathways for humans and wildlife: a synthesis of current knowledge and key gaps in understanding, Environ. Toxicol. Chem. 40 (2021) 631–657, https://doi.org/10.1002/ETC.4935.

[15] N.M. DeLuca, M. Angrish, A. Wilkins, K. Thayer, E.A. Cohen Hubal, Human exposure pathways to poly- and perfluoroalkyl substances (PFAS) from indoor media: a systematic review protocol, Environ. Int. 146 (2021), https://doi.org/10.1016/J.ENVINT.2020.106308.

[16] G.G. Deme, D. Ewusi-Mensah, O.A. Olagbaju, E.S. Okeke, C.O. Okoye, E.C. Odii, O. Ejeromedoghene, E. Igun, J.O. Onyekwere, O.K. Oderinde, E. Sanganyado, Macro problems from microplastics: Toward a sustainable policy framework for managing microplastic waste in Africa, Science of the Total Environment 804 (2022) 150170, https://doi.org/10.1016/j.scitotenv.2021.150170.

[17] A. Di Nisio, I. Sabovic, U. Valente, S. Tescari, M.S. Rocca, D. Guidolin, S. Dall'Acqua, L. Acquasaliente, N. Pozzi, M. Plebani, A. Garolla, C. Foresta, Endocrine disruption of androgenic activity by perfluoroalkyl substances: clinical and experimental evidence, J. Clin. Endocrinol. Metab. 104 (2019) 1259–1271, https://doi.org/10.1210/JC.2018-01855.

[18] J.L. Domingo, I. Ericson-Jogsten, G. Perelló, M. Nadal, B. Van Bavel, A. Kärrman, Human exposure to perfluorinated compounds in Catalonia, Spain: contribution of drinking water and fish and shellfish, J. Agric. Food Chem. 60 (2012) 4408–4415, https://doi.org/10.1021/JF300355C/ASSET/IMAGES/MEDIUM/JF-2012-00355C_0004.GIF.

[19] John Nweze Ekene, Prince Chidike Ezeorba Timothy, E.S. Okeke, Christian Ezike Tobechukwu, Nwuga Chijioke, Dietary Exposure to Polycyclic Aromatic Hydrocarbons and the Probabilistic Health Risk Assessment of Eating Roasted Yams (Dioscorea Species) by African Population, Current Applied Science & Technology xx (2023) e0258411, https://doi.org/10.55003/cast.2023.258411.

[20] M.P. Elizalde, S. Gómez-Lavín, A.M. Urtiaga, Migration of perfluorinated compounds from paperbag to Tenax® and lyophilised milk at different temperatures, Int. J. Environ. Anal. Chem. 98 (2018) 1423–1433, https://doi.org/10.1080/03067319.2018.1562062.

[21] M.P. Elizalde, S. Gómez-Lavín, A.M. UrtiagaMigration of perfluorinated compounds from paperbag to Tenax® and lyophilised milk at different temperatures 98 https://doi. Org. /10. 1080/03067319. 2018. 1562062 , 2019, 1423–1433, 10.1080/03067319.2018.1562062.

[22] EPA, 2022. 2022 EPA Health Advisory levels for four PFAS 331–702.

[23] A. Ernst, N. Brix, L.L.B. Lauridsen, J. Olsen, E.T. Parner, Z. Liew, L.H. Olsen, C. H. Ramlau-Hansen, Exposure to perfluoroalkyl substances during fetal life and pubertal development in boys and girls from the Danish National Birth cohort, Environ. Health Perspect. 127 (2019), https://doi.org/10.1289/EHP3567.

[24] European CommissionRegulation (EC) No 10/2011 of 14 January 2011 on Plastic Materials and Articles Intended to Come into Contact with Food 12 . J. Eur. Union , 2011, Regulation (EC) No 10/ of 14 January 2011 on Plastic Materials and Articles Intended to Come into Contact with Food 20111–89.

[25] European Commission, 2020. Commission Staff Working Document Poly- and perfluoroalkyl substances (PFAS). Luxembourg.

[26] European Food Safety Authority, Results of the monitoring of perfluoroalkylated substances in food in the period 2000–2009, EFSA J. 9 (2011).

[27] C.G. Eze, C.E. Nwankwo, S. Dey, S. Sundaramurthy, E.S. Okeke, Food chain microplastics contamination and impact on human health: a review. Environmental Chemistry Letters, Springer International Publishing, 2024, https://doi.org/10.1007/s10311-024-01734-2.

[28] T.P.C. Ezeorba, K.I. Chukwudozie, C.O. Okoye, E.S. Okeke, A.L. Ezugwu, E. G. Anaduaka, Biofungicides: Classification, Applications and Limitations, Biofungicides Eco-Safety Futur. Trends (2023) 12–39, https://doi.org/10.1201/9781003287575-2.

[29] P.A. Fair, B. Wolf, N.D. White, S.A. Arnott, K. Kannan, R. Karthikraj, J.E. Vena, Perfluoroalkyl substances (PFASs) in edible fish species from Charleston Harbor and tributaries, South Carolina, United States: exposure and risk assessment, Environ. Res. 171 (2019) 266–277, https://doi.org/10.1016/J.ENVRES.2019.01.021.

[30] W. Feng, T. Xu, J. Zuo, M. Luo, G. Mao, Y. Chen, Y. Ding, E.S. Okeke, X. Wu, L. Yang, The potential mechanisms of TBBPA bis(2-hydroxyethyl) ether induced developmental neurotoxicity in juvenile zebrafish (Danio rerio), Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology (2022) 109530, https://doi.org/10.1016/J.CBPC.2022.109530.

[31] R. Fengler, M. Schlummer, L. Gruber, D. Fiedler, N. Weise, Migration of fluorinated telomer alcohols (FTOH) from food contact materials into food at elevated temperatures, Organomet. Compd. Vol. 73 (2011) 939–942.

[32] H. Fiedler, T. Kennedy, B.J. Henry, A critical review of a recommended analytical and classification approach for organic fluorinated compounds with an emphasis on per- and polyfluoroalkyl substances, Integr. Environ. Assess. Manag. 17 (2021) 331–351, https://doi.org/10.1002/IEAM.4352.

[33] H. Gardener, Q. Sun, P. Grandjean, PFAS concentration during pregnancy in relation to cardiometabolic health and birth outcomes, Environ. Res. 192 (2021) 110287, https://doi.org/10.1016/J.ENVRES.2020.110287.

[34] W.A. Gebbink, A. Glynn, P.O. Darnerud, U. Berger, Perfluoroalkyl acids and their precursors in Swedish food: the relative importance of direct and indirect dietary exposure, Environ. Pollut. 198 (2015) 108–115, https://doi.org/10.1016/J.ENVPOL.2014.12.022.

[35] S.D. Geiger, P. Yao, M.G. Vaughn, Z. Qian, PFAS exposure and overweight/obesity among children in a nationally representative sample, Chemosphere 268 (2021), https://doi.org/10.1016/J.CHEMOSPHERE.2020.128852.

[36] S. Genualdi, W. Young, L. Dejager, T. Begley, Method development and validation of per-and polyfluoroalkyl substances in foods from FDA's total diet study program, J. Agric. Food Chem. 69 (2021) 5599–5606, https://doi.org/10.1021/ACS.JAFC.1C01777/SUPPL_FILE/JF1C01777_SI_001.PDF.

[37] S. Genualdi, J. Beekman, K. Carlos, C.M. Fisher, W. Young, L. DeJager, T. Begley, Analysis of per- and poly-fluoroalkyl substances (PFAS) in processed foods from FDA's Total Diet Study, Anal. Bioanal. Chem. 414 (2022) 1189–1199, https://doi.org/10.1007/S00216-021-03610-2/TABLES/2.

[38] J. Glüge, M. Scheringer, I.T. Cousins, J.C. Dewitt, G. Goldenman, D. Herzke, R. Lohmann, C.A. Ng, X. Trier, Z. Wang, An overview of the uses of per- and polyfluoroalkyl substances (PFAS), Environ. Sci. Process. Impacts 22 (2020) 2345–2373, https://doi.org/10.1039/D0EM00291G.

[39] K. Granby, J.T. Håland, Per- and polyfluorinated alkyl substances (PFAS) in paper and board Food Contact, Mater. Sel. Samples Nor. Mark. (2018) 2017.

[40] Granby, K., Tesdal Haland, J., 2018. Per- and polyfluorinated alkyl substances (PFAS) in paper and board Food Contact Materials - Selected samples from the Norwegian market 2017.

[41] P. Grandjean, C.A. Gade Timmermann, M. Kruse, F. Nielsen, P.J. Vinholt, L. Boding, C. Heilmann, K. Mølbak, Severity of COVID-19 at elevated exposure to perfluorinated alkylates, PLoS One 15 (2020), https://doi.org/10.1371/JOURNAL.PONE.0244815.

[42] J. Ji, L. Song, J. Wang, Z. Yang, H. Yan, T. Li, L. Yu, L. Jian, F. Jiang, J. Li, J. Zheng, K. Li, Association between urinary per- and poly-fluoroalkyl substances and COVID-19 susceptibility, Environ. Int. 153 (2021), https://doi.org/10.1016/J.ENVINT.2021.106524.

[43] J.M. Jian, D. Chen, F.J. Han, Y. Guo, L. Zeng, X. Lu, F. Wang, A short review on human exposure to and tissue distribution of per- and polyfluoroalkyl substances (PFASs), Sci. Total Environ. 636 (2018) 1058–1069, https://doi.org/10.1016/J.SCITOTENV.2018.04.380.

[44] G.R. Johnson, PFAS in soil and groundwater following historical land application of biosolids, Water Res 211 (2022) 118035, https://doi.org/10.1016/J.WATRES.2021.118035.

[45] P.D. Jones, W. Hu, W. De Coen, J.L. Newsted, J.P. Giesy, Binding of perfluorinated fatty acids to serum proteins, Environ. Toxicol. Chem. 22 (2003) 2639–2649, https://doi.org/10.1897/02-553.

[46] L.S. Kjeldsen, E.C. Bonefeld-Jørgensen, Perfluorinated compounds affect the function of sex hormone receptors, Environ. Sci. Pollut. Res. Int. 20 (2013) 8031–8044, https://doi.org/10.1007/S11356-013-1753-3.

[47] J.E. Lee, K. Choi, Perfluoroalkyl substances exposure and thyroid hormones in humans: epidemiological observations and implications, Ann. Pediatr. Endocrinol. Metab. 22 (2017) 6, https://doi.org/10.6065/APEM.2017.22.1.6.

[48] S. Lee, S. Kim, J. Park, H. Kim, G. Choi, S.C.-S. of the TPerfluoroalkyl substances (PFASs) in breast milk from Korea: time-course trends, influencing factors, and infant exposure Elsevier (, n.d.), 2018.

[49] Y.J. Lee, H.W. Jung, H.Y. Kim, Y.J. Choi, Y.A. Lee, Early-life exposure to per- and poly-fluorinated alkyl substances and growth, adiposity, and puberty in children: a systematic review, Front. Endocrinol. (Lausanne). 12 (2021) 1096, https://doi.org/10.3389/FENDO.2021.683297/BIBTEX.

[50] R. Letcher, G. Su, J. Moore, L.W.-S. of the TPerfluorinated sulfonate and carboxylate compounds and precursors in herring gull eggs from across the Laurentian Great Lakes of North America: Temporal Elsevier U., 2015 , 2015.

[51] Y. Liu, A. Li, S. Buchanan, W. Liu, Exposure characteristics for congeners, isomers, and enantiomers of perfluoroalkyl substances in mothers and infants, Environ. Int. 144 (2020) 106012, https://doi.org/10.1016/J.ENVINT.2020.106012.

[52] M. Llorca, M. Farré, Y. Picó, M.L. Teijón, J.G. Álvarez, D. Barceló, Infant exposure of perfluorinated compounds: levels in breast milk and commercial baby food, Environ. Int. 36 (2010) 584–592, https://doi.org/10.1016/J.ENVINT.2010.04.016.

[53] M. Luo, Z. Wu, T. Xu, Y. Ding, X. Qian, E.S. Okeke, G. Mao, Y. Chen, W. Feng, X. Wu, The neurotoxicity and mechanism of TBBPA-DHEE exposure in mature zebrafish (Danio rerio), Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology (2023) 109572, https://doi.org/10.1016/J.CBPC.2023.109572.

[54] M. Luo, C. Song, J. Zuo, W. Feng, C. Wu, X. Geng, E.S. Okeke, G. Mao, Y. Chen, T. Zhao, X. Wu, Neurodevelopmental toxicity and molecular mechanism of environmental concentration of tetrabromobisphenol A bis (2- hydroxyethyl) ether exposure to sexually developing male SD rats, Chemosphere 353 (2024) 141378, https://doi.org/10.1016/j.chemosphere.2024.141378.

[55] S.J. Lupton, K.L. Dearfield, J.J. Johnston, S. Wagner, J.K. Huwe, Perfluorooctane sulfonate plasma half-life determination and long-term tissue distribution in beef cattle (Bos taurus), J. Agric. Food Chem. 63 (2015) 10988–10994, https://doi.org/10.1021/ACS.JAFC.5B04565/SUPPL_FILE/JF5B04565_SI_001.PDF.

[56] C. Moreta, M.T. Tena, Fast determination of perfluorocompounds in packaging by focused ultrasound solid–liquid extraction and liquid chromatography coupled to quadrupole-time of flight mass spectrometry, J. Chromatogr. A 1302 (2013) 88–94, https://doi.org/10.1016/J.CHROMA.2013.06.024.

[57] I. Navarro, A. de la Torre, P. Sanz, M.Á. Porcel, J. Pro, G. Carbonell, M. Martínez, los Á. de, Uptake of perfluoroalkyl substances and halogenated flame retardants by crop plants grown in biosolids-amended soils, Environ. Res. 152 (2017) 199–206, https://doi.org/10.1016/J.ENVRES.2016.10.018.

[58] C. Nielsen, A. Jöud, Susceptibility to COVID-19 after high exposure to perfluoroalkyl substances from contaminated drinking water: an ecological study from Ronneby, Sweden, Int. J. Environ. Res. Public Health 18 (2021), https://doi.org/10.3390/IJERPH182010702.

[59] J.N. Nkoh, O. Oderinde, N. Oshogwue, G.A. Kifle, E.S. Okeke, O. Ejeromedoghene, C.L. Mgbechidinma, Recent perspective of antibiotics remediation: A review of the principles, mechanisms, and chemistry controlling remediation from aqueous media, Science of the Total Environment (2023), https://doi.org/10.1016/j.scitotenv.2023.163469.

[60] J.N. Nkoh, C. Shang, E.S. Okeke, O. Ejeromedoghene, O. Oderinde, N.O. Etafo, C. L. Mgbechidinma, O.C. Bakare, E.F. Meugang, Antibiotics soil-solution chemistry: A review of environmental behavior and uptake and transformation by plants, Journal of Environmental Management 354 (2024) 120312, https://doi.org/10.1016/j.jenvman.2024.120312.

[61] C.W. Noorlander, S.P.J. Van Leeuwen, J.D. Te Biesebeek, M.J.B. Mengelers, M. J. Zeilmaker, Levels of perfluorinated compounds in food and dietary intake of PFOS and PFOA in the Netherlands, J. Agric. Food Chem. 59 (2011) 7496–7505, https://doi.org/10.1021/JF104943P.

[62] NTP, 2016. Immunotoxicity Associated with Exposure to Perfluorooctanoic Acid (PFOA) or Perfluorooctane Sulfonate (PFOS) [WWW Document]. URL ⟨https://ntp.niehs.nih.gov/whatwestudy/assessments/noncancer/completed/pfoa⟩ (accessed 3.2.24).

[63] E.S. Okeke, I.U. Okagu, C.O. Okoye, T.P.C. Ezeorba, The use of calcium carbide in food and fruit ripening: potential mechanisms of toxicity to humans and future prospects, Toxicology 468 (2022) 153112, https://doi.org/10.1016/j.tox.2022.153112.

[64] E.S. Okeke, K.I. Chukwudozie, R. Nyaruaba, R.E. Ita, Antibiotic resistance in aquaculture and aquatic organisms: a review of current nanotechnology applications for sustainable management. Environmental Science and Pollution Research, Springer Berlin, Heidelberg, 2022, https://doi.org/10.1007/s11356-022-22319-y.

[65] E.S. Okeke, E. John Nweze, C. Samuel Ubani, T. Prince Chidike Ezeorba, A. Vivian Arazu, Health Risk Assessment of Heavy Metals Associated with Terminalia catappa Fruit Consumption Obtained from an Automobile Workshop Cluster in Nsukka, Nigeria, Current Applied Science and Technology 22 (2021) 1–15, https://doi.org/10.55003/cast.2022.02.22.006.

[66] E.S. Okeke, T.P.C. Ezeorba, G. Mao, Y. Chen, W. Feng, X. Wu, Nano-enabled agrochemicals/materials: Potential human health impact, risk assessment, management strategies and future prospects, Environmental Pollution 295 (2022) 118722, https://doi.org/10.1016/j.envpol.2021.118722.

[67] E.S. Okeke, T.P.C. Ezeorba, C. Yao, M. Guanghua, F. Weiwei, W. Xiangyang, Association of tetrabromobisphenol A (TBBPA) with micro / nano-plastics: A review of recent findings on ecotoxicological and health impacts, Science of the Total Environment 927 (2024) 172308, https://doi.org/10.1016/j.scitotenv.2024.172308.

[68] E.S. Okeke, T. Prince, C. Ezeorba, C. Obinwanne, Y. Chen, G. Mao, W. Feng, Environmental and health impact of unrecovered API from pharmaceutical manufacturing wastes: A review of contemporary treatment, recycling and management strategies, Sustainable Chemistry and Pharmacy 30 (2022) 100865, https://doi.org/10.1016/j.scp.2022.100865.

[69] E.S. Okeke, T. Prince, C. Ezeorba, Y. Chen, G. Mao, W. Feng, X. Wu, Ecotoxicological and health implications of microplastic - associated biofilms: a recent review and prospect for turning the hazards into benefits, Environmental Science and Pollution Research (2022), https://doi.org/10.1007/s11356-022-22612-w.

[70] E.S. Okeke, C.O. Okoye, E.O. Atakpa, R.E. Ita, R. Nyaruaba, C.L. Mgbechidinma, O.D. Akan, Microplastics in agroecosystems-impacts on ecosystem functions and food chain, Resources Conservation & Recycling 177 (2022) 105961, https://doi.org/10.1016/j.resconrec.2021.105961.

[71] E.S. Okeke, H. Bin, M. Guanghua, C. Yao, Z. Zhengjia, Q. Xian, W. Xiangyang, F. Weiwei, Review of the environmental occurrence, analytical techniques, degradation and toxicity of TBBPA and its derivatives, Environmental Research 206 (2022) 112594, https://doi.org/10.1016/j.envres.2021.112594.

[72] E.S. Okeke, K.I. Chukwudozie, C.I. Addey, J.O. Okoro, T.P.C. Ezeorba, E. O. Atakpa, C.O. Okoye, C.O. Nwuche, Micro and nanoplastics ravaging our agroecosystem: A review of occurrence, fate, ecological impacts, detection, remediation, and prospects, Heliyon (2023) 0, https://doi.org/10.1016/J.HELIYON.2023.E13296.

[73] E.S. Okeke, W. Feng, M. Luo, G. Mao, Y. Chen, T. Zhao, X. Wu, L. Yang, RNA-Seq analysis offers insight into the TBBPA-DHEE-induced endocrine-disrupting effect and neurotoxicity in juvenile zebrafish (Danio rerio), General and Comparative Endocrinology 350 (2024) 114469, https://doi.org/10.1016/j.ygcen.2024.114469.

[74] E.S. Okeke, O. Ejeromedoghene, C.I. Addey, O. Atakpa, S.F. Bello, T. Prince, C. Ezeorba, K.I. Chukwudozie, C.O. Okoye, Panacea for the nanoplastic surge in Africa: A state-of-the-art review, Heliyon 0 (2022) e11562, https://doi.org/10.1016/J.HELIYON.2022.E11562.

[75] E.S. Okeke, A. Enochoghene, B.C. Ezeudoka, S.D. Kaka, Y. Chen, G. Mao, C. ThankGod Eze, W. Feng, X. Wu, A review of heavy metal risks around e-waste sites and comparable municipal dumpsites in major African cities: Recommendations and future perspectives, Toxicology 501 (2024) 153711, https://doi.org/10.1016/j.tox.2023.153711.

[76] E.S. Okeke, X. Qian, J. Che, G. Mao, Y. Chen, H. Xu, Y. Ding, Z. Zeng, X. Wu, W. Feng, Transcriptomic sequencing reveals the potential molecular mechanism by which Tetrabromobisphenol A bis (2-hydroxyethyl ether) exposure exerts developmental neurotoxicity in developing zebrafish (Danio rerio), Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology 262 (2022) 109467, https://doi.org/10.1016/j.cbpc.2022.109467.

[77] E.S. Okeke, W. Feng, C. Song, G. Mao, Y. Chen, H. Xu, X. Qian, M. Luo, X. Wu, L. Yang, Transcriptomic profiling reveals the neuroendocrine-disrupting effect and toxicity mechanism of TBBPA-DHEE exposure in zebrafish during sexual development (Danio rerio), Science of the Total Environment (2023) 160089, https://doi.org/10.1016/J.SCITOTENV.2022.160089.

[78] E.S. Okeke, W. Feng, G. Mao, Y. Chen, X. Qian, M. Luo, H. Xu, X. Qiu, X. Wu, L. Yang, A transcriptomic-based analysis predicts the neuroendocrine disrupting effect on adult male and female zebrafish (Danio rerio) following long-term exposure to Tetrabromobisphenol A bis(2-hydroxyethyl) ether, Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology (2023) 109527, https://doi.org/10.1016/J.CBPC.2022.109527.

[79] E.S. Okeke, M. Luo, W. Feng, Y. Zhang, G. Mao, Y. Chen, Z. Zeng, X. Qian, L. Sun, L. Yang, X. Wu, Transcriptomic profiling and differential analysis revealed the neurodevelopmental toxicity mechanisms of zebrafish (Danio rerio) larvae in response to tetrabromobisphenol A bis(2–hydroxyethyl) ether (TBBPA-DHEE) exposure, Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology 259 (2022) 109382, https://doi.org/10.1016/J.CBPC.2022.109382.

[80] E.S. Okeke, C. Olisah, A. Malloum, K.A. Adegoke, J.O. Ighalo, J. Conradie, C. R. Ohoro, J.F. Amaku, K.O. Oyedotun, N.W. Maxakato, K.G. Akpomie, Ecotoxicological impact of dinotefuran insecticide and its metabolites on non-targets in agroecosystem: Harnessing nanotechnology- and bio-based management strategies to reduce its impact on non-target ecosystems, Environmnetal Research (2023) 117870, https://doi.org/10.1016/J.ENVRES.2023.117870.

[81] E.S. Okeke, O.A. Olagbaju, C.O. Okoye, C.I. Addey, K.I. Chukwudozie, J.O. Okoro, G.G. Deme, D. Ewusi-Mensah, E. Igun, O. Ejeromedoghene, E.C. Odii, O. Oderinde, V.C. Iloh, S. Abesa, Microplastic burden in Africa: a review of occurrence, impacts, and sustainability potential of bioplastics, Chemical Engineering Journal Advances (2022) 100402, https://doi.org/10.1016/J.CEJA.2022.100402.

[82] C.O. Okoye, R. Nyaruaba, R. Ekeng, U. Okon, C. Izuma, C.C. Ebido, A. Oluwole, E. S. Okeke, K. Ikechukwu, Antibiotic resistance in the aquatic environment: Analytical techniques and interactive impact of emerging contaminants, Environmental Toxicology and Pharmacology 96 (2022) 103995, https://doi.org/10.1016/j.etap.2022.103995.

[83] Charles Obinwanne Okoye, E.S. †Okeke, K.C. Okoye, D. Echude, F.A. Andong, K. I. Chukwudozie, H.U. Okoye, C.D. Ezeonyejiaku, Occurrence and fate of pharmaceuticals, personal care products (PPCPs) and pesticides in African water systems: A need for timely intervention, Heliyon 8 (2022) e09143, https://doi.org/10.1016/j.heliyon.2022.e09143.

[84] Charles Obinwanne Okoye, C.I. Addey, O. Oderinde, J.O. Okoro, J.Y. Uwamungu, C.K. Ikechukwu, E.S. Okeke, O. Ejeromedoghene, E.C. Odii, Toxic Chemicals and Persistent Organic Pollutants Associated with Micro-and Nanoplastics Pollution, Chemical Engineering Journal Advances 11 (2022) 100310, https://doi.org/10.1016/j.ceja.2022.100310.

[85] G. Patlewicz, A.M. Richard, A.J. Williams, C.M. Grulke, R. Sams, J. Lambert, P. D. Noyes, M.J. DeVito, R.N. Hines, M. Strynar, A. Guiseppi-Elie, R.S. Thomas, A chemical category-based prioritization approach for selecting 75 per- and polyfluoroalkyl substances (PFAS) for tiered toxicity and toxicokinetic testing, Environ. Health Perspect. 127 (2019), https://doi.org/10.1289/EHP4555.

[86] D.J. Piekarski, K.R. Diaz, M.W. McNerney, Perfluoroalkyl chemicals in neurological health and disease: human concerns and animal models, Neurotoxicology 77 (2020) 155–168, https://doi.org/10.1016/J.NEURO.2020.01.001.

[87] G. Pitter, M. Zare Jeddi, G. Barbieri, M. Gion, A.S.C. Fabricio, F. Daprà, F. Russo, T. Fletcher, C. Canova, Perfluoroalkyl substances are associated with elevated blood pressure and hypertension in highly exposed young adults, Environ. Heal. A Glob. Access Sci. Source 19 (2020) 1–11, https://doi.org/10.1186/S12940-020-00656-0/TABLES/3.

[88] D.F.K. Rawn, C. Ménard, S.Y. Feng, Method development and evaluation for the determination of perfluoroalkyl and polyfluoroalkyl substances in multiple food matrices, Food Addit. Contam. - Part A Chem. Anal. Control. Expo. Risk Assess. 39 (2022) 752–776, https://doi.org/10.1080/19440049.2021.2020913/SUPPL_FILE/TFAC_A_2020913_SM3804.DOCX.

[89] B.P. Rickard, I. Rizvi, S.E. Fenton, Per- and poly-fluoroalkyl substances (PFAS) and female reproductive outcomes: PFAS elimination, endocrine-mediated effects, and disease, Toxicology 465 (2022) 153031, https://doi.org/10.1016/J.TOX.2021.153031.

[90] M.B. Rosen, K.P. Das, J. Rooney, B. Abbott, C. Lau, J.C. Corton, PPARα-independent transcriptional targets of perfluoroalkyl acids revealed by transcript profiling, Toxicology 387 (2017) 95–107, https://doi.org/10.1016/J.TOX.2017.05.013.

[91] B. Ruffle, U. Vedagiri, D. Bogdan, M. Maier, C. Schwach, C. Murphy-Hagan, Perfluoroalkyl Substances in U.S. market basket fish and shellfish, Environ. Res. 190 (2020) 109932, https://doi.org/10.1016/J.ENVRES.2020.109932.

[92] L.A. Schaider, S.A. Balan, A. Blum, D.Q. Andrews, M.J. Strynar, M.E. Dickinson, D.M. Lunderberg, J.R. Lang, G.F. Peaslee, Fluorinated compounds in U.S. fast food packaging, Environ. Sci. Technol. Lett. 4 (2017) 105–111, https://doi.org/10.1021/ACS.ESTLETT.6B00435.

[93] L.A. Schaider, S.A. Balan, A. Blum, D.Q. Andrews, M.J. Strynar, M.E. Dickinson, D.M. Lunderberg, J.R. Lang, G.F. Peaslee, Fluorinated compounds in U.S. fast food packaging, Environ. Sci. Technol. Lett. 4 (2017) 105–111, https://doi.org/10.1021/ACS.ESTLETT.6B00435/ASSET/IMAGES/LARGE/EZ-2016-00435Z_0001.JPEG.

[94] L.A. Schaider, S.A. Balan, A. Blum, D.Q. Andrews, M.J. Strynar, M.E. Dickinson, D.M. Lunderberg, J.R. Lang, G.F. Peaslee, Fluorinated compounds in U.S. fast food packaging, Environ. Sci. Technol. Lett. 4 (2017) 105–111, https://doi.org/10.1021/ACS.ESTLETT.6B00435.

[95] D.P. Scher, J.E. Kelly, C.A. Huset, K.M. Barry, R.W. Hoffbeck, V.L. Yingling, R. B. Messing, Occurrence of perfluoroalkyl substances (PFAS) in garden produce at homes with a history of PFAS-contaminated drinking water, Chemosphere 196 (2018) 548–555, https://doi.org/10.1016/J.CHEMOSPHERE.2017.12.179.

[96] M. Schlummer, L. Gruber, R. Fengler, D. Fiedler, G. Wolz, How poly-and perfluoroalkyl substances (PFAS) may enter our food from food contact materials (FCM), Proc. PERFOOD Proj. Meet. Amst., Neth. 7 (2011) 15–17.

[97] D. Schrenk, M. Bignami, L. Bodin, J.K. Chipman, J. del Mazo, B. Grasl-Kraupp, C. Hogstrand, L. Hoogenboom, J.C. Leblanc, C.S. Nebbia, E. Nielsen, E. Ntzani, A. Petersen, S. Sand, C. Vleminckx, H. Wallace, L. Barregård, S. Ceccatelli, J. P. Cravedi, T.I. Halldorsson, L.S. Haug, N. Johansson, H.K. Knutsen, M. Rose, A. C. Roudot, H. Van Loveren, G. Vollmer, K. Mackay, F. Riolo, T. Schwerdtle, Risk to human health related to the presence of perfluoroalkyl substances in food, EFSA J. 18 (2020) e06223, https://doi.org/10.2903/J.EFSA.2020.6223.

[98] L. Schultes, G.F. Peaslee, J.D. Brockman, A. Majumdar, S.R. McGuinness, J. T. Wilkinson, O. Sandblom, R.A. Ngwenyama, J.P. Benskin, Total fluorine measurements in food packaging: how do current methods perform, Environ. Sci. Technol. Lett. 6 (2019) 73–78, https://doi.org/10.1021/ACS.ESTLETT.8B00700/ASSET/IMAGES/LARGE/EZ-2018-00700N_0002.JPEG.

[99] N. Seltenrich, PFAS in food packaging: a hot, greasy exposure, Environ. Health Perspect. 128 (2020) 1–2, https://doi.org/10.1289/EHP6335.

[100] E. Shahsavari, D. Rouch, L.S. Khudur, D. Thomas, A. Aburto-Medina, A.S. Ball, Challenges and current status of the biological treatment of pfas-contaminated soils, Front. Bioeng. Biotechnol. 8 (2021) 1493, https://doi.org/10.3389/FBIOE.2020.602040/BIBTEX.

[101] J. Shoaff, G.D. Papandonatos, A.M. Calafat, A. Chen, B.P. Lanphear, S. Ehrlich, K. T. Kelsey, J.M. Braun, Prenatal exposure to perfluoroalkyl substances, Environ. Epidemiol. 2 (2018) e010, https://doi.org/10.1097/EE9.0000000000000010.

[102] S. Squadrone, V. Ciccotelli, M. Prearo, L. Favaro, T. Scanzio, C. Foglini, M. C. Abete, Perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA): emerging contaminants of increasing concern in fish from Lake Varese, Italy, Environ. Monit. Assess. 187 (2015) 1–7, https://doi.org/10.1007/S10661-015-4686-0/FIGURES/2.

[103] H.M. Starnes, K.D. Rock, T.W. Jackson, S.M. Belcher, A critical review and meta-analysis of impacts of per- and polyfluorinated substances on the brain and behavior, Front. Toxicol. 4 (2022), https://doi.org/10.3389/FTOX.2022.881584.

[104] K. Steenland, A. Winquist, PFAS and cancer, a scoping review of the epidemiologic evidence, Environ. Res. 194 (2021), https://doi.org/10.1016/J.ENVRES.2020.110690.

[105] E.M. Sunderland, X.C. Hu, C. Dassuncao, A.K. Tokranov, C.C. Wagner, J.G. Allen, A review of the pathways of human exposure to poly- and perfluoroalkyl substances (PFASs) and present understanding of health effects, 2018, J. Expo. Sci. Environ. Epidemiol. 292 (29) (2018) 131–147, https://doi.org/10.1038/s41370-018-0094-1.

[106] J.T. Szilagyi, V. Avula, R.C. Fry, Perfluoroalkyl substances (PFAS) and their effects on the placenta, pregnancy and child development: a potential mechanistic role for placental peroxisome proliferator-activated receptors (PPARs), Curr. Environ. Heal. Rep. 7 (2020) 222, https://doi.org/10.1007/S40572-020-00279-0.

[107] T. Teymourian, T. Teymoorian, E. Kowsari, S. Ramakrishna, A review of emerging PFAS contaminants: sources, fate, health risks, and a comprehensive assortment of recent sorbents for PFAS treatment by evaluating their mechanism, 2021, Res. Chem. Intermed. 4712 (47) (2021) 4879–4914, https://doi.org/10.1007/S11164-021-04603-7.

[108] S.A. Tittlemier, K. Pepper, C. Seymour, J. Moisey, R. Bronson, X.L. Cao, R. W. Dabeka, Dietary exposure of canadians to perfluorinated carboxylates and perfluorooctane sulfonate via consumption of meat, fish, fast foods, and food items prepared in their packaging, J. Agric. Food Chem. 55 (2007) 3203–3210, https://doi.org/10.1021/JF0634045.

[109] D.X. Trier, C. Taxvig, A.K. Rosenmai, G. PedersenPFAS in Paper and Board for Food Contact Copenhagen, Denmark , Nordic Council of Ministers , 2017.

[110] X. Trier, C. Taxvig, A.K. Rosenmai, G.A. PedersenPFAS in paper and board for food contact: options for risk management of poly-and perfluorinated substances Nordic Council of Ministers , 2018.

[111] I.A.L.P. van Beijsterveldt, B.D. van Zelst, K.S. de Fluiter, S.A.A. van den Berg, M. van der Steen, A.C.S. Hokken-Koelega, Poly- and perfluoroalkyl substances (PFAS) exposure through infant feeding in early life, Environ. Int. 164 (2022) 107274, https://doi.org/10.1016/J.ENVINT.2022.107274.

[112] Y. Wang, R. Vestergren, Y. Shi, D. Cao, L. Xu, Y. Cai, X. Zhao, F. Wu, Identification, tissue distribution, and bioaccumulation potential of cyclic perfluorinated sulfonic acids isomers in an airport impacted ecosystem, Environ. Sci. Technol. 50 (2016) 10923–10932, https://doi.org/10.1021/ACS.EST.6B01980.

[113] Z. Wang, J.C. Dewitt, C.P. Higgins, I.T. Cousins, A never-ending story of per- and polyfluoroalkyl substances (PFASs), Environ. Sci. Technol. 51 (2017) 2508–2518, https://doi.org/10.1021/ACS.EST.6B04806/ASSET/IMAGES/LARGE/ES-2016-048069_0002.JPEG.

[114] WHO, 2020. Salt Reduction [WWW Document].

[115] K. Winkens, R. Vestergren, U. Berger, I.T. Cousins, Early life exposure to per- and polyfluoroalkyl substances (PFASs): a critical review, Emerg. Contam. 3 (2017) 55–68, https://doi.org/10.1016/J.EMCON.2017.05.001.

[116] P.L. Yao, D.J. Ehresman, J.M.C. Rae, S.C. Chang, S.R. Frame, J.L. Butenhoff, G. L. Kennedy, J.M. Peters, Comparative in vivo and in vitro analysis of possible estrogenic effects of perfluorooctanoic acid, Toxicology 326 (2014) 62–73, https://doi.org/10.1016/J.TOX.2014.10.008.

[117] G. Yuan, H. Peng, C. Huang, J. Hu, Ubiquitous occurrence of fluorotelomer alcohols in eco-friendly paper-made food-contact materials and their implication for human exposure, Environ. Sci. Technol. 50 (2016) 942–950, https://doi.org/10.1021/acs.est.5b03806.

[118] I. Zabaleta, E. Bizkarguenaga, A.I.-… of C. AFocused ultrasound solid–liquid extraction for the determination of perfluorinated compounds in fish, vegetables and amended soil Elsevier U., 2014 , 2014.

[119] I. Zabaleta, E. Bizkarguenaga, A.P.-… of C. ASimultaneous determination of perfluorinated compounds and their potential precursors in mussel tissue and fish muscle tissue and liver samples by liquid Elsevier U., 2015 , 2015.

[120] I. Zabaleta, E. Bizkarguenaga, D. Bilbao, N.E.- TalantaFast and simple determination of perfluorinated compounds and their potential precursors in different packaging materials Elsevier U., 2016 , 2016.

[121] I. Zabaleta, N. Negreira, E. Bizkarguenaga, A.P.-F. ChemistryScreening and identification of per-and polyfluoroalkyl substances in microwave popcorn bags Elsevier U., 2017 , 2017.

[122] P. Zheng, Y. Liu, Q. An, X. Yang, S. Yin, L.Q. Ma, W. Liu, Prenatal and postnatal exposure to emerging and legacy per-/polyfluoroalkyl substances: levels and transfer in maternal serum, cord serum, and breast milk, Sci. Total Environ. 812 (2022), https://doi.org/10.1016/J.SCITOTENV.2021.152446.