World Journal of Advanced Research and Reviews

eISSN: 2581-9615 CODEN (USA): WJARAI

Cross Ref DOI: 10.30574/wjarr

Journal homepage: https://wjarr.com/

(Research Article)

Check for updates

Tracing PFAS Contamination Across the Food Supply Chain: Assessing Foodborne Risks from Production to Consumption

Jumoke Ajayi *

Bemidji State University / 2404 Bemidji Ave. Bemidji, MN. 56601.

World Journal of Advanced Research and Reviews, 2025, 28(02), 278-287

Publication history: Received on 20 September 2025; revised on 27 October 2025; accepted on 30 October 2025

Article DOI: https://doi.org/10.30574/wjarr.2025.28.2.3676

Abstract

Per- and polyfluoroalkyl substances (PFAS) have emerged as a critical food safety and public health concern due to their persistence, bio accumulative nature, and widespread presence across the global food supply chain. This study investigates PFAS contamination pathways from agricultural production to final consumption, emphasizing the mechanisms through which these “forever chemicals” infiltrate soil, water, crops, livestock, and processed foods. Industrial emissions, contaminated irrigation water, biosolids used as fertilizers, and food packaging materials are identified as key contributors to PFAS entry into the food system. Once absorbed, PFAS compounds accumulate in edible tissues and plant matter, leading to chronic human exposure through dietary intake. The paper evaluates recent findings on PFAS concentration levels in various food categories, including seafood, dairy, meat, and grains, alongside their toxicological implications such as endocrine disruption, immune suppression, and carcinogenicity. Analytical techniques such as liquid chromatography-tandem mass spectrometry (LC-MS/MS) are discussed for accurate detection and quantification of PFAS in complex food matrices. Furthermore, this study highlights the gaps in existing food safety regulations, calling for harmonized global standards, improved monitoring frameworks, and sustainable agricultural practices to limit PFAS contamination. Overall, the research underscores the urgent need for cross-sector collaboration and policy reform to safeguard human health and maintain food system integrity in the face of persistent PFAS pollution.

Keywords: PFAS; Food Safety; Foodborne Risk; Contamination Pathways; Farm-To-Fork; Bioaccumulation; Public Health; Environmental Pollution; Food Packaging; LC-MS/MS; Regulatory Standards

1. Introduction

Per- and polyfluoroalkyl substances (PFAS) are a large class of synthetic chemicals that have become a major environmental and public health concern due to their extreme persistence, bio accumulative nature, and widespread presence in everyday products [1]. Commonly referred to as “forever chemicals,” PFAS are used in numerous industrial and consumer applications including non-stick cookware, waterproof textiles, firefighting foams, and food packaging materials because of their resistance to heat, water, and oil [2]. However, this same chemical stability that makes PFAS commercially valuable also renders them resistant to natural degradation, allowing them to accumulate in soil, water, air, and living organisms over time [3].

In recent years, growing evidence has shown that PFAS can contaminate the food supply chain through multiple pathways [4]. Agricultural activities that use contaminated irrigation water, biosolids, or fertilizers can introduce PFAS into crops and livestock [5]. Similarly, industrial discharge and polluted groundwater can affect aquatic ecosystems, leading to elevated PFAS levels in fish and seafood [6]. Beyond primary production, food-contact materials such as packaging, coatings, and processing equipment serve as additional sources of contamination, as PFAS can migrate into

* Corresponding author: Jumoke Ajayi

food products during processing, storage, and distribution [7]. The cumulative effect of these exposures contributes to the continuous ingestion of PFAS through daily diets, making food one of the most significant routes of human exposure.

The health implications of PFAS contamination are profound and far-reaching. Numerous studies have linked chronic PFAS exposure to endocrine disruption, immune system suppression, developmental delays, reproductive issues, and certain cancers [8]. Given their long biological half-lives and ability to accumulate in human tissues, even low-level exposures pose potential long-term health risks [9]. These concerns have prompted international regulatory agencies, including the U.S. Environmental Protection Agency (EPA), the European Food Safety Authority (EFSA), and the World Health Organization (WHO), to intensify monitoring and establish safety thresholds for PFAS in food and drinking water [10].

This paper aims to trace the occurrence, sources, and migration pathways of PFAS across the food supply chain from agricultural production to final consumption while assessing the associated foodborne risks to human health. By examining contamination mechanisms, analytical detection methods, and existing policy responses, this research underscores the urgent need for coordinated global efforts to mitigate PFAS exposure. Ultimately, understanding how PFAS move through the farm-to-fork continuum is essential for developing sustainable solutions that ensure food safety, protect public health, and preserve environmental integrity.

2. Migration of Per- and Polyfluoroalkyl Substances (PFAS) from Food Packaging and Contact Materials into Food Products

Food contact materials (FCMs) may transfer dangerous chemical compounds into food through a migration mechanism. PFAS had been detected in several paperboards and food wrappers by total fluorine analysis as a PFAS surrogate [11]. Migration is an inevitable process influenced by several factors that adhere to Fick's diffusion laws. The release of PFAS is contingent upon: (1) the material's capacity to emit PFAS, (2) the conditions of food contact, including temperature and duration of exposure, (3) the characteristics 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, quantified as the distribution coefficient between the material and the food [12].

The pathways of exposure during processing and packaging reflect current PFAS production and usage. Fast food wrappers and other grease- and water-resistant packaging contain PFAS, which can permeate food and elevate dietary exposure. The predominant PFAS now employed in food packaging are short-chain variants and fluorotelomer-based derivatives. The migration is affected by the concentration, mass fractions, type, and length of the PFAS chain, as well as the type of food, even during a brief interaction between the material and the food. The chain length of PFAS influences its bioaccumulation potential and toxicity.

Longer-chain PFAS, including perfluorooctanesulfonic acid (PFOS) and perfluorooctanoic acid (PFOA), exhibit greater persistence and enhanced bioaccumulation potential compared to shorter-chain PFAS. Longer-chain PFAS are more likely to accumulate in the food chain and provide a heightened risk of negative health effects in humans. The temperature and duration of contact can affect the migration of PFAS from food packaging materials into food [11]. Increased temperatures can expedite the transfer of PFAS, particularly from non-stick cookware and fast-food packaging, into food. Extended contact durations with food further heighten the likelihood of PFAS migration into the meal.

The particular impacts of these factors on food contamination may differ based on the type of food and the packaging material utilized. A study indicated that cooking eggs in a non-stick pan at elevated temperatures led to increased PFAS migration into the eggs compared to using a stainless-steel pan. A study indicated that fast food packaging materials containing PFAS may contaminate meals, particularly when the food is hot and oily [13].

The initial stage involves the release of PFAS from the material's surface, contingent upon whether PFAS is absorbed into the substance or merely resides on its surface. The surface must be moist to dissolve the bonds that adhere the substance to the surface and facilitate the release of the chemicals [14], [15]. The second phase of PFAS migration transpires when the chemicals solubilize in food. Due to their status as environmental contaminants, detecting PFAS in food can be difficult, as they may be present in the product prior to processing or packaging. Due to their simpler analytical matrices compared to food, it is recommended to employ food simulants for migration assays [16]. Furthermore, it is essential to verify that the materials employed by the laboratory were devoid of microbial contamination. In several studies, a Teflon-free paper filter is employed as a replacement [11], [10].

The subsequent factors were employed for migration assessments: For example, given the expectation of elevated temperatures during food preparation, the migration conditions utilized for a dish intended for microwave heating were 70 ºC for 2 h [17]. For samples incapable of retaining liquids, such as baking paper, a segment of the sample is positioned under the lid of a stainless-steel cylinder, which is subsequently sealed with a solid food simulant, such as Tenax®, and subjected to the appropriate temperature and duration in the oven [11], [10]. Before applying the simulant and subjecting the samples to the appropriate temperature for the necessary length to facilitate migration [17], square cuts of the samples, including muffin wrappers, pizza boxes, and hot beverage cups, are prepared. This complies with Commission Regulation (EU) No 10/2011 [18].

2.1. Factors Influencing PFAS Migration in Food

2.1.1. Moisture Content

The transfer of PFAS into food is affected by the moisture level present in the meal. PFAS are characterized by their hydrophobic nature, indicating a tendency to oppose water while exhibiting an affinity for fats and oils. This can lead to their accumulation in the adipose tissues of animals and facilitate their migration from food packaging materials into fatty foods. Fengler et al. [19] examined the movement of two samples of muffin masses in their investigation. The FTOH measurements were observed to be lower for the sample with elevated moisture content compared to the muffin with reduced moisture content. The authors assert that the FTOH evaporates, resulting in a decreased concentration in the food, which explains this variance [19].

2.1.2. Lipid content

PFAS are predominantly found in protein-rich foods, such as liver, game meat, livestock, and fish, due to their propensity to interact with proteins. In migration testing, fat content exerts a more significant influence than protein levels, as these components are utilized to enhance the material's resistance to lipids and are commonly included in the packaging of fast food and ultra-processed products. To illustrate that PFAS do not disperse uniformly across various food kinds, Choi et al. [11], [10] analyzed 312 samples, encompassing pans, bakeware, electric rice cookers, grills, and baking papers. PFODA and PFNA, the analytes predominantly detected in n-heptane and 50% ethanol, respectively, had the highest proportions in this instance. PFODA exhibited a concentration of 3.05 μg L^{-1} in the n-heptane simulant, whereas PFNA demonstrated a concentration of 2.12 μg L^{-1} in the same simulant. The data indicate that alcoholic beverages and fatty foods are the primary dietary sources with a high likelihood of PFC migration [11], [10]. Elizalde et al. [20] shown that the migration of perfluorinated chemicals, specifically PFHXA, PFHPA, PFOA, PFNA, PFDA, PFTRDA, and PFTEDA, from paper bags to Tenax® and lyophilized milk was more pronounced in whole milk compared to low-fat milk. Low-fat milk contained 50% less fat than whole milk, even though both varieties were freeze-dried [20].

Emulsified meals have elevated migration levels compared to non-emulsified fatty diets. In their research on the migration of PFAS in emulsified foods, Begley et al. [5] found that the migration rate was up to 50 times higher in emulsified foods such as butter compared to non-emulsified fats like oil. The migration of PFAS at 100 °C is anticipated to increase when the proportion of ethanol to water escalates from 10% to 30%, consistent with the migration seen using food simulants.

2.1.3. Acidity

PFAS exhibit greater stability in acidic settings, facilitating its release into acidic foods. Conversely, in simpler environments, such as certain vegetables, PFAS are less prone to transfer into the meal. Research indicates that the pH of food can affect the migration of PFAS into it [1]. The migration of PFAS into food was greater in acidic conditions (pH 4.0) than in neutral conditions (pH 7.0). Acidic beverages, such as orange juice, exhibit elevated levels of PFAS contamination relative to other beverages with a more neutral ph.

2.1.4. Salt concentration

The WHO estimates daily salt consumption to be between 10 and 12 grams. This include both precooked meals and salt incorporated during cooking and processing. It is thus intriguing to understand the impact of salt concentration on the migration of perfluoro alkylated compounds in food [21]. Studies indicate that sodium chloride allegedly accelerates the transfer of PFAS [1]. NaCl can disrupt the repulsive interactions between PFAS and surfaces, facilitating the migration or transfer of PFAS onto food. Comparative analysis of PFOS and PFOA migration from non-stick utensils to food revealed that migration rates were elevated in salt-added foods compared to salt-free diets.

3. Analytical Approaches for Detecting and Quantifying PFAS in Food Products and Packaging Materials

Humans are exposed to PFAS mostly through food consumption. Consequently, PFAS identified in food-contact packaging materials have garnered significant attention in recent years. PFAS employed in food contact boards and paper have demonstrated persistence, bioaccumulation, and significant toxicity. Analytical methods are necessary to ascertain the origins of PFAS exposure through board and paper, and to assess their contaminant components and degradation byproducts. Consequently, new fluorinated chemicals may arise, and a comprehensive approach for the detection and identification of all PFAS is lacking [22]. Due to the complexity of polyfluorinated surfactants as mixtures, they present an analytical challenge and necessitate advanced analytical techniques to identify all possible constituents [23].

The total fluorine in samples can be quantified using several non-specific approaches, including some spectroscopic techniques such as nuclear magnetic resonance (NMR) and sliding spark spectroscopy [24]. Moreover, experimental neutron activation analysis is an excellent method for quantifying total fluorine [25]. Identifying PFAS is crucial, as fluorine may be present in other fluorinated compounds or as inorganic fluorine. Due to their low quantities and the presence of many other PFAS in these samples, identifying these chemicals is problematic [26]. Liquid chromatography coupled with mass spectrometry (LC-MS or UPLC-MS), together with tandem mass spectrometry, has been employed to quantify PFAS in food-contact materials [11], [10], [27].

Liquid chromatography linked to triple quadrupole mass spectrometry (LC-QqQ) and liquid chromatography connected to quadrupole time-of-flight mass spectrometry (LC-QTOF) has recently been developed for the detection of trace quantities of PFAS in food packaging materials [28]. Fluorine was identified in food packaging paper samples at a concentration exceeding 16 $nmol/cm^2$ [29]. Liquid chromatography coupled with mass spectrometry (LC-MS) was developed by researchers in Sweden and Denmark for the quantification of perfluoroalkyl acids (PFAA), some perfluoro octane sulfonate (PFOS) derivatives, and total organic fluorine [30]. Thirteen of the 35 examined items, which included muffin packaging, popcorn bags, fast-food packaging, and baking dishes, contained PFAS.

Newly produced paper fiber inherently lacks PFAS. To prevent packing from absorbing moisture and grease, a coating is often applied to paper and cardboard. They may also be incorporated throughout the recycling process into the final product. Various analytical approaches are utilized for the detection and quantification of PFAS in food packaging materials, contingent upon the specific study type. Nonetheless, liquid chromatography coupled with triple quadrupole mass spectrometry (LC-MS/MS) is the most sensitive and selective method available.

4. Dietary pathways on PFAS

The primary human exposure pathways to PFAS encompass several food sources, including: (1) Ingesting food contaminated with PFAS, either via direct exposure to PFAS-laden materials during production, processing, packing, and storage, or through the contamination of soil, water, and air utilized in food production; (2) Ingesting food from animals that have been subjected to PFAS exposure, whether via contaminated feed or environmental factors; (3) Ingesting seafood contaminated with PFAS, as these substances can bioaccumulate throughout the aquatic food chain; (4) Utilizing cookware, food packaging, or other food contact materials (FCMs) that include per- and polyfluoroalkyl substances (PFAS), which may leach into food during preparation or storage; (5) Consuming water polluted with PFAS for culinary, drinking, or food processing purposes.

In the last 70 years, numerous businesses have employed PFAS, a category of synthetic organofluoride compounds that remain persistent in the environment. Toxicological study indicates that exposure to certain PFAS, especially long-chain variants, may jeopardize the reproductive, endocrine, and immunological systems in people. This discussion will focus on a theoretical model of PFAS exposure, detailing the sources, transport processes, and human exposure pathways. Point sources and non-point sources are the primary contributors to human PFAS exposure. Industrial activities, including fire training and response sites, are associated with primary point sources, but non-point sources may encompass food products, food packaging, and potable water. The transport paths of PFAS, contingent upon their chemical composition, may encompass surface water runoff, long-range air deposition, and groundwater migration. All of these procedures may taint agricultural products and ultimately expose humans to PFAS.

European research indicates that drinking water is the primary source of PFAS exposure to people, surpassed only by point-source contamination. Lakes, groundwater, and rivers serve as drinking water sources that may be contaminated with PFAS leaking from industrial origins. Specifically, because to their high solubility in water, PFAS have been identified in numerous water sources next to probable point sources, such as fire-fighting and manufacturing operations [31]. The EPA has established far tougher warning levels, with updated Health warning Levels of 0.004 ng/L for PFOA and 0.02 ng/L for PFOS. The revised standards demonstrate the EPA's dedication to safeguarding public health from the possible hazards linked to exposure to these contaminants in drinking water. These health warnings are non-regulatory and non-enforceable; yet, they provide essential health protection information for regulators and the public [32]. The revised recommendations demonstrate the EPA's dedication to safeguarding public health from the hazards linked to PFAS exposure in drinking water [32].

Moreover, there exists a significant danger of exposure to PFAS-contaminated sewage sludge (biosolids) and recycled water from wastewater treatment plants, commonly employed in agriculture [33]. Nonetheless, comprehensive research is required to comprehend the proportionate impact of various PFAS sources on the human diet. Owing to its unique functional properties, PFAS are utilized in several consumer products globally. Grease-resistant paper, non-stick cookware, fast food wrappers, and retail packaging are but a few potential exposure pathways for PFAS. In compliance with FDA regulations, producers in the USA have voluntarily ceased the use of long-chain PFAS and do not intentionally include them into food packaging. Short-chain PFAS and fluorinated acrylate polymers are permitted for usage in packaging and several commercial applications.

Occupational exposure constitutes a significant avenue for PFAS exposure. Individuals employed in sectors where PFAS is manufactured or utilized in food packaging materials are also at risk [34]. The bioaccumulation potential of PFAS has been established, and it escalates with longer chain lengths. Specific PFAS chemicals have been shown to impact human health by affecting thyroid and kidney function, causing immunosuppression, and producing detrimental effects on reproduction and development. Chronic diseases associated with perfluoro octane sulfonate (PFOA) include renal and testicular cancers, hypercholesterolemia, and ulcerative colitis [33].

Bioaccumulation at the source and exposure during processing and packing are the two primary mechanisms via which PFAS infiltrate food. Long-term applications of PFAS are generally indicated by bioaccumulation pathways, which may also encompass biosolids industrial ashes and sludges rich in nutrients that enhance agricultural and soil productivity. PFAS in biosolids may leak into groundwater, hence contaminating drinking water [35]. They may be assimilated by crops, so exposing humans to them via food [36].

PFAS can accumulate in various plants and animals consumed as food, exhibiting distinct methods and patterns of accumulation. In plants, PFAS can accumulate via absorption from polluted soil and water, as well as through air deposition. Upon absorption by the plant, PFAS can be transported to many plant sections, including consumable components like leaves, fruits, and seeds. The deposition of PFAS in vegetation is affected by variables like plant species, soil composition, pH levels, and moisture content. In animals, PFAS can accumulate via nutritional consumption, as well as through inhalation or cutaneous contact with polluted water, soil, or air. PFAS can bioaccumulate in several animal tissues, such as muscle, liver, and adipose tissue. Long-chain PFAS, particularly PFOS, exhibit a significant propensity to bioaccumulate in beef and fish, in contrast to the accumulation of short-chain PFAS in crops [37]. Moreover, in contrast to other persistent chemicals, PFAS preferentially accumulate in proteins rather than lipids inside muscle, kidney, and liver tissues. The buildup of PFAS in animals is affected by species, age, sex, and food. The accumulation patterns of PFAS in various plants and animals can change based on the individual kinds of PFAS and their physicochemical characteristics. Long-chain PFAS are more prone to bioaccumulation in animal tissues compared to short-chain PFAS, although specific PFAS types, such PFOS, exhibit greater accumulation in particular fish species, including tuna and salmon.

In 2016, the National Toxicology Program (NTP) performed an extensive assessment of human, animal, and laboratory research examining the immunotoxin effects of PFOA and PFOS. This comprehensive evaluation revealed that both PFOA and PFOS are considered to have possible immune-related hazards to humans. The research identified substantial evidence connecting both drugs to the inhibition of the antibody response. Furthermore, there was insufficient data indicating that PFOA may result in diminished resistance to infectious infections, exacerbated hypersensitivity-related consequences, and a higher prevalence of autoimmune diseases.

Likewise, PFOS was linked to the inhibition of natural killer cell function. Likewise, perfluoroalkyl compounds have shown the capacity to influence thyroid hormone levels in rats, and research has established associations between blood perfluoroalkyl concentrations and thyroid hormone levels in human epidemiological investigations. Although research on the mechanisms of thyroid hormone disruption by perfluoroalkyls is sparse, existing information indicates that these compounds may influence thyroid function by binding to the thyroid hormone receptor or altering the expression of genes pertinent to thyroid function and regulation. Studies indicate that several perfluoroalkyls can associate with the human thyroid hormone receptor in cultivated GH2 cancer cells, as demonstrated by molecular docking tests [38].

5. Effects on Human Health

Upon exposure, PFAS may persistently accumulate in many regions of the human body. The health effects linked to this exposure can only be assessed if these levels reach toxicity [14]. Given the prevalence of PFAS in human blood, it is the predominant sample matrix utilized for screening PFAS toxicity in human serum globally. Numerous studies have examined PFAS concentrations in human blood, revealing that persons with occupational or other forms of exposure have greater PFAS levels than the general population, which comprises individuals with no known exposure. Jian et al. [39] evaluated 87 studies and determined that the concentration of PFAS in human blood ranges from 0.01 to 10,400 ng/ml, with fisherman in China exhibiting the highest levels. Silva et al. [40] evaluated various publications and noted that the concentration of PFAS in occupationally exposed persons was 1–4 times more in magnitude than that of the general population. Piekarski et al. [41] analyzed 35 articles and concluded that the worldwide concentrations of perfluoroalkyl acids (PFAAs) in adult serum of the general population ranged from 0.5 to 35.5 ng/ml, whereas levels in occupationally exposed individuals varied from 12.7 to 2190 ng/ml.

Recent peer-reviewed research indicates that exposure to PFAS might adversely affect human health. These findings indicate that PFAS can directly induce disease or compromise the immune system, hence exacerbating the pathogenicity of pre-existing conditions. The prevalent human health effects encompass reproductive issues such as diminished fertility and elevated blood pressure in pregnant women [42], [43], heightened cancer risk (e.g., renal and testicular malignancies) [44], hormonal dysregulation [45], [46], increased cholesterol levels contributing to obesity [4], and raised blood pressure and hypertension in significantly exposed young adults [47].

In addition to inducing sickness and other health repercussions in adults, maternal, newborn, and prenatal exposure to PFAS has been recorded worldwide [48]. PFAS have been identified in infant serum, cord serum, mother serum, and breast milk, indicating placental transfer of PFAS during pre- and postnatal care [49], [50]. In a study, the exposure levels of PFAS were ranked as follows: maternal serum > cord serum > breast milk [50]. Breast milk has been determined to constitute 83–99% of the total PFAS intake by babies. Nonetheless, according to current scientific understanding, the advantages of nursing surpass the risks associated with PFAS exposure from contaminated milk [51]. One should see a physician to accurately assess the hazards if apprehensive. In addition to maternal transfers, newborns are at an elevated risk of PFAS exposure because to their increased consumption of water, food, and air relative to their body weight compared to adults [52].

Finally, it is crucial to acknowledge that the health effects associated with PFAS exposure are challenging to categorize for several reasons: a limited number of PFAS compounds have been studied despite the existence of thousands, each with unique toxicity levels; individual exposure to PFAS can differ across various life stages; and the usage and types of PFAS evolve over time, complicating the assessment of the impact of a singular PFAS exposure on human health. Notwithstanding these constraints, scientific data and ongoing surveillance are essential for determining the causes and effects of both novel and current PFAS, as well as safeguarding public health from associated risks.

6. Future Perspective

PFAS are artificial chemicals, and novel compounds are consistently being developed and incorporated into the existing category. This presents a possible health hazard, as most of these novel PFAS are developed as alternatives to those now in use. Exposure to PFAS can lead to numerous health consequences, including cancer, thyroid hormone alteration, immune system impairment, and developmental and reproductive damage. The primary mode of exposure is via contaminated food and water sources. Nonetheless, the toxicity and characteristics of these alternative PFAS and their precursors remain little comprehended, hence requiring additional investigation to formulate efficient remediation strategies. Thus, the identification, characterization, and description of these novel PFAS in the environment pose significant challenges.

Human exposure to PFAS is influenced by factors such as lifestyle and dietary habits, resulting in diverse exposure pathways across different locations. Consequently, comprehensive investigations on exposure pathways and associated health risks should be undertaken across various worldwide regions. To mitigate the impact of PFAS, a comprehensive approach for identifying its sources and pathways is essential. The minimal amounts at which PFAS commonly exist in the environment present a considerable obstacle to its removal, necessitating precise and effective sampling, analytical, and determination methodologies. Gas and liquid chromatographic techniques are the most dependable methods for laboratory-scale analysis. The existing techniques for detecting, treating, and evaluating PFAS are ineffective and unsustainable, and there is insufficient understanding of their environmental elimination.

Regulating the use of PFAS in food production and minimizing its environmental emission is essential for ensuring food safety. This necessitates rigorous oversight and examination of food products to identify any PFAS contamination. The food business bears the need to implement sustainable procedures that reduce the utilization of PFAS in food production and processing. The utilization of PFAS in food production is an increasing issue for public health experts worldwide. Prioritizing food safety necessitates the regulation of PFAS and the implementation of sustainable strategies to mitigate their environmental release. This will mitigate the incidence of foodborne illnesses and guarantee that folks have access to secure and nutritious food supply.

7. Conclusion

Tracing PFAS contamination across the food supply chain reveals a complex and persistent challenge that extends from environmental sources to the consumer's plate. The widespread use of PFAS in industrial processes, agricultural inputs, and food packaging materials has led to their infiltration into multiple stages of food production and distribution. Once released, these "forever chemicals" persist in soil, water, crops, and animal tissues, ultimately entering human diets through bioaccumulation and long-term exposure. The cumulative effect poses significant public health risks, including endocrine disruption, immune dysfunction, developmental toxicity, and potential carcinogenicity. Addressing this issue requires a coordinated and multidisciplinary approach that bridges environmental science, food safety regulation, and public health policy. Strengthening monitoring systems, improving analytical capabilities (such as LC-MS/MS detection), and enforcing stricter contamination limits are critical steps toward minimizing PFAS exposure. Moreover, promoting safer alternatives in manufacturing, improving waste management, and encouraging transparent labeling of PFAS-free products can reduce contamination at its source. Ultimately, safeguarding the integrity of the food system depends on proactive collaboration between researchers, policymakers, industry stakeholders, and consumers. By integrating science-driven decision-making with sustainable practices, society can reduce PFAS burdens across the food chain—ensuring safer food, cleaner environments, and healthier communities for generations to come.

References

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

[2] Akan O.D., Udofia G.E., Okeke E.S., Mgbechidinma C.L., Okoye C.O., Zoclanclounon Y.A.B., Atakpa E.O., Adebanjo O.O. Plastic waste: Status, degradation and microbial management options for Africa. Journal of Environmental Management. 2021;292.

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

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

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

[6] Blake B.E., Fenton S.E. 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. 2020;443.

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

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

[9] Chen L., Tong C., Huo X., Zhang J., Tian Y. Prenatal exposure to perfluoroalkyl and polyfluoroalkyl substances and birth outcomes: a longitudinal cohort with repeated measurements. Chemosphere. 2021;267

[10] Choi H., Bae I.A., Choi J.C., Park S.J., Kim M.K. Perfluorinated compounds in food simulants after migration from fluorocarbon resin-coated frying pans, baking utensils, and non-stick baking papers on the Korean market.

[11] Schaider L.A., Balan S.A., Blum A., Andrews D.Q., Strynar M.J., Dickinson M.E., Lunderberg D.M., Lang J.R., Peaslee G.F. Fluorinated compounds in U.S. fast food packaging. Environ. Sci. Technol. Lett. 2017;4:105–111.

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

[13] Seltenrich N. PFAS in food packaging: a hot, greasy exposure. Environ. Health Perspect. 2020;128:1–2.

[14] Tittlemier S.A., Pepper K., Seymour C., Moisey J., Bronson R., Cao X.L., Dabeka R.W. 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. 2007;55:3203–3210.

[15] Yuan G., Peng H., Huang C., Hu J. Ubiquitous occurrence of fluorotelomer alcohols in eco-friendly paper-made food-contact materials and their implication for human exposure. Environ. Sci. Technol. 2016;50:942–950.

[16] European Food Safety Authority Results of the monitoring of perfluoroalkylated substances in food in the period 2000–2009. EFSA J. 2011;9

[17] 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.

[18] 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.

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

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

[21] Winkens K., Vestergren R., Berger U., Cousins I.T. Early life exposure to per- and polyfluoroalkyl substances (PFASs): a critical review. Emerg. Contam. 2017;3:55–68.

[22] 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.

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

[24] Schaider L.A., Balan S.A., Blum A., Andrews D.Q., Strynar M.J., Dickinson M.E., Lunderberg D.M., Lang J.R., Peaslee G.F. Fluorinated compounds in U.S. fast food packaging. Environ. Sci. Technol. Lett. 2017;4:105–111.

[25] Schultes L., Peaslee G.F., Brockman J.D., Majumdar A., McGuinness S.R., Wilkinson J.T., Sandblom O., Ngwenyama R.A., Benskin J.P. Total fluorine measurements in food packaging: how do current methods perform. Environ. Sci. Technol. Lett. 2019;6:73–78.

[26] Fiedler H., Kennedy T., Henry B.J. 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. 2021;17:331–351.

[27] lizalde M.P., Gómez-Lavín S., Urtiaga A.M. Migration of perfluorinated compounds from paperbag to Tenax® and lyophilised milk at different temperatures. Int. J. Environ. Anal. Chem. 2018;98:1423–1433.

[28] Moreta C., Tena M.T. 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. 2013;1302:88–94.

[29] Schaider L.A., Balan S.A., Blum A., Andrews D.Q., Strynar M.J., Dickinson M.E., Lunderberg D.M., Lang J.R., Peaslee G.F. Fluorinated compounds in U.S. fast food packaging. Environ. Sci. Technol. Lett. 2017;4:105–111.

[30] Teymourian T., Teymoorian T., Kowsari E., Ramakrishna S. A review of emerging PFAS contaminants: sources, fate, health risks, and a comprehensive assortment of recent sorbents for PFAS treatment by evaluating their mechanism. Res. Chem. Intermed. 2021;4712(47):4879–4914.

[31] Di Nisio A., Sabovic I., Valente U., Tescari S., Rocca M.S., Guidolin D., Dall'Acqua S., Acquasaliente L., Pozzi N., Plebani M., Garolla A., Foresta C. Endocrine disruption of androgenic activity by perfluoroalkyl substances: clinical and experimental evidence. J. Clin. Endocrinol. Metab. 2019;104:1259–1271.

[32] Ernst A., Brix N., Lauridsen L.L.B., Olsen J., Parner E.T., Liew Z., Olsen L.H., Ramlau-Hansen C.H. Exposure to perfluoroalkyl substances during fetal life and pubertal development in boys and girls from the Danish National Birth cohort. Environ. Health Perspect. 2019;127

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

[34] Teymourian T., Teymoorian T., Kowsari E., Ramakrishna S. A review of emerging PFAS contaminants: sources, fate, health risks, and a comprehensive assortment of recent sorbents for PFAS treatment by evaluating their mechanism. Res. Chem. Intermed. 2021;4712(47):4879–4914.

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

[36] Shahsavari E., Rouch D., Khudur L.S., Thomas D., Aburto-Medina A., Ball A.S. Challenges and current status of the biological treatment of pfas-contaminated soils. Front. Bioeng. Biotechnol. 2021;8:1493.

[37] Lupton S.J., Dearfield K.L., Johnston J.J., Wagner S., Huwe J.K. Perfluorooctane sulfonate plasma half-life determination and long-term tissue distribution in beef cattle (Bos taurus) J. Agric. Food Chem. 2015;63:10988–10994.

[38] Rosen M.B., Das K.P., Rooney J., Abbott B., Lau C., Corton J.C. PPARα-independent transcriptional targets of perfluoroalkyl acids revealed by transcript profiling. Toxicology. 2017;387:95–107.

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

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

[41] Piekarski D.J., Diaz K.R., McNerney M.W. Perfluoroalkyl chemicals in neurological health and disease: human concerns and animal models. Neurotoxicology. 2020;77:155–168.

[42] Gardener H., Sun Q., Grandjean P. PFAS concentration during pregnancy in relation to cardiometabolic health and birth outcomes. Environ. Res. 2021;192

[43] Szilagyi J.T., Avula V., Fry R.C. 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. 2020;7:222.

[44] Steenland K., Winquist A. PFAS and cancer, a scoping review of the epidemiologic evidence. Environ. Res. 2021;194

[45] Di Nisio A., Sabovic I., Valente U., Tescari S., Rocca M.S., Guidolin D., Dall'Acqua S., Acquasaliente L., Pozzi N., Plebani M., Garolla A., Foresta C. Endocrine disruption of androgenic activity by perfluoroalkyl substances: clinical and experimental evidence. J. Clin. Endocrinol. Metab. 2019;104:1259–1271.

[46] Lee J.E., Choi K. Perfluoroalkyl substances exposure and thyroid hormones in humans: epidemiological observations and implications. Ann. Pediatr. Endocrinol. Metab. 2017;22:6.

[47] Pitter G., Zare Jeddi M., Barbieri G., Gion M., Fabricio A.S.C., Daprà F., Russo F., Fletcher T., Canova C. Perfluoroalkyl substances are associated with elevated blood pressure and hypertension in highly exposed young adults. Environ. Heal. A Glob. Access Sci. Source. 2020;19:1–11.

[48] Liu Y., Li A., Buchanan S., Liu W. Exposure characteristics for congeners, isomers, and enantiomers of perfluoroalkyl substances in mothers and infants. Environ. Int. 2020;144

[49] Squadrone S., Ciccotelli V., Prearo M., Favaro L., Scanzio T., Foglini C., Abete M.C. Perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA): emerging contaminants of increasing concern in fish from Lake Varese, Italy. Environ. Monit. Assess. 2015;187:1–7.

[50] Zheng P., Liu Y., An Q., Yang X., Yin S., Ma L.Q., Liu W. 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. 2022;812

[51] van Beijsterveldt I.A.L.P., van Zelst B.D., de Fluiter K.S., van den Berg S.A.A., van der Steen M., Hokken-Koelega A.C.S. Poly- and perfluoroalkyl substances (PFAS) exposure through infant feeding in early life. Environ. Int. 2022;164

[52] Winkens K., Vestergren R., Berger U., Cousins I.T. Early life exposure to per- and polyfluoroalkyl substances (PFASs): a critical review. Emerg. Contam. 2017;3:55–68.