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Review

The Alarming Effects of Per- and Polyfluoroalkyl Substances (PFAS) on One Health and Interconnections with Food-Producing Animals in Circular and Sustainable Agri-Food Systems

Gerald C. Shurson

Department of Animal Science, University of Minnesota, St. Paul, MN 55108, USA; shurs001@umn.edu

Abstract

Per- and polyfluoroalkyl substances (PFAS) are synthetically produced chemicals that are causing a major One Health crisis. These "forever chemicals" are widely distributed globally in air, water, and soil, and because they are highly mobile and extremely difficult to degrade in the environment. They cause additional health concerns in a circular bioeconomy and food system that recycles and reuses by-products and numerous types of waste materials. Uptake of PFAS by plants and food-producing animals ultimately leads to the consumption of PFAS-contaminated food that is associated with numerous adverse health and developmental effects in humans. Contaminated meat, milk, and eggs are some of the main sources of human PFAS exposure. Although there is no safe level of PFAS exposure, maximum tolerable PFAS consumption guidelines have been established for some countries. However, there is no international PFAS monitoring system, and there are no standardized international guidelines and mechanisms to prevent the consumption of PFAS-contaminated foods. Urgent action is needed to stop PFAS production except for critical uses, implementing effective water-purification treatments, preventing spreading sewage sludge on land and pastures used to produce food, and requiring marketers and manufacturers to use packaging that is free of PFAS.

Keywords: atmosphere; food; human health; livestock; per- and polyfluoroalkyl substances; plants; regulations; remediation; soil; sustainability; water

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1. Introduction

Perfluoroalkyl and polyfluoroalkyl substances (PFAS) are a group of more than 15,000 types of human-made chemicals [1] that have become another unintended consequence of human innovation and have created a major One Health crisis that is polluting all aspects of our environment and poisoning billions of people around the world. In addition, widespread PFAS contamination in the environment is linked to several Sustainable Development Goals (SDG) including SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production, and SDG 14 (Life Below Water). The extreme persistence and mobility of PFAS in aquatic environments makes them a significant concern for water pollution. Unfortunately, societal awareness of the significance, global prevalence, and detrimental health effects of PFAS contamination in plants, animals, humans, and the environment is not as well-known as other major One Health concerns such as antibiotic resistance, zoonotic diseases, food safety, climate change,

and other environmental contamination issues. There are more than 200 applications of PFAS in industrial and consumer products involving 64 different categories and subcategories of uses including many well-known applications such as in fire-fighting foams; oil, water, and stain repellents for carpets, upholstery, and clothing; cleaning products; non-stick cookware; paints, varnishes, and sealants; personal care products including cosmetics, shampoo, lotions, and dental floss; and food packaging including fast-food containers, pizza boxes, and candy wrappers (Table 1; [2,3]). Other lesser-known PFAS use categories that have not been reported in the scientific literature include applications in consumer products such as ammunition, guitar strings, climbing ropes, and in artificial turf [2]. Because PFAS can repel water and lipids, they are extremely stable and difficult to degrade in the environment [4]. The recalcitrant nature of PFAS has resulted in them often being described as "forever chemicals" due to their ability to persist in the environment for an unknown amount of time, causing bioaccumulation and subsequent numerous toxic effects in the environment [5]. However, there is little, if any, information regarding the amounts of the many types of PFAS that have been, and will be released, transformed, and accumulated in the environment and living organisms over time [6].

Table 1. Industrial and consumer products containing various types of PFAS (adapted from [2,3]).

Product Category	Application
Automotive	Treatment for external surfaces and internal leather coatings, textiles, and carpets; used in mechanical components, seals and lubricants
Aviation and aerospace	Additives for hydraulic fluids; insulators and sleeves
Biocides	Active compounds in plant growth regulators; active or inert emulsifiers, solvents, carriers, wetting agents; aerosol propellants in pesticides
Building and construction	Coatings of architectural materials; additives in coatings, paints, dyes, stains, and sealants; weathering, flame, and soil resistant coatings for cables and wiring; plastic foams including polystyrene and polyurethane; floor coverings, coated woods; solar panels and glass
Electronics	Flame retardants; insulators and welding materials; semiconductor chips; electroplating; liquids and greases used as lubricants in electronics; ionic liquids used in lithium batteries
Energy	Film for solar panels
Fire prevention	Fire-extinguishing foams; materials for fire-fighting equipment, protective clothes, and fuel repellents
Food processing and packaging	Non-stick cooking pans and food storage containers; water and oil repellent paper, bags, and food packaging materials
Household products	Propellant gases, refrigerants, and extinguishing agents; surfactants in floor-cleaning products; non-stick coatings and treatments for textiles, leather, carpets; car waxes
Medical products	Stain-resistant and water repellent materials; X-ray film; surgical patches, biocompatible human implants, and medical prosthesis; pharmaceuticals
Metal plating	Wetting agent and anti-mist agents
Oil wells and mining	Surfactants in oil wells and mining floatation; lining of gas pipes; drilling fluids
Personal care products	Cosmetics, makeup, nail polish, shampoo, dental floss, and skin lotions; sun protection
Sports equipment	Ski waxes; waterproofing sprays for outdoor water repellent clothing; climbing ropes; artificial turf
Textiles, leather, and clothing products	Coatings to create oil, water, and stain-repellent properties

The widespread use and high mobility of PFAS enables them to be transported over long distances, resulting in widespread distribution and bioaccumulation that increases concentrations of these chemicals in almost every geographic region in the world, and in all types of environmental matrices including air, groundwater, freshwater, marine water, and soil [3]. Because the atmosphere, water, and soil environments are interconnected

and inseparable, there is constant PFAS movement, recycling, and exposure of plants, animals, and humans to PFAS. This interconnection creates multiple environmental exposure pathways in which PFAS contaminate food and drinking-water supplies, which are the major pathways of human exposure and toxicity [7]. Contaminated pastures, forages, grain and oilseed crops, and drinking water that are consumed by food-producing animals are the primary sources of PFAS that result in contaminated meat, milk, and eggs consumed by humans, which can lead to numerous adverse health effects [8,9]. Furthermore, PFAS chemicals are also found in wastewater [10] and landfills [11], and are concentrated in sewage sludge, which is commonly applied to agricultural soils as a fertilizer [12,13]. Dairy and beef cattle grazing pastures or consuming forages and other feedstuffs where biosolids from sewage treatment facilities have been applied have elevated PFAS concentrations in the meat and milk they produce [14]. Manure is the primary route of excretion from livestock and poultry consuming PFAS-contaminated feed and drinking water [15]. When PFAS-contaminated animal manure is applied to agricultural soils, it enables the recycling of these recalcitrant chemicals back into the food-production system [16]. Therefore, as we continue to transition from a linear "take, make, consume, dispose, and pollute" economy toward a circular bioeconomy and agri-food system that recycles and reuses waste materials (e.g., food loss and waste, agri-industrial by-products, and animal manure), in which food-producing animals play an essential role, we need to understand the multiple pathways of PFAS exposure to attempt to break their recycling and reduce human exposure. Therefore, the purpose of this review is to summarize (1) the chemical characteristics of PFAS, (2) the various types of consumer products that contain PFAS, (3) evidence that PFAS are a serious human-health threat, (4) environmental PFAS exposure routes for food-producing animals, and (5) current PFAS regulations, remediation, and exposure prevention strategies.

2. Methods

A systematic literature search was conducted using Google to identify relevant peer-reviewed publications, including original research studies, case studies, and literature reviews, along with documents from non-government organizations, government agencies, and regulatory publications associated with PFAS. Documents from PFAS manufacturers and end users and various public media sources were excluded. Additional publications were obtained by reviewing and identifying references cited and cross-referenced in the 77 systematic and scoping literature reviews, meta-analyses, data summaries, and numerous articles. Many key words were used to search for scholarly articles and other articles of relevance and interest on the extent of contamination and effects of PFAS in the atmosphere, water, soil, environment, plants, crops, fruits, vegetables, human health, food, meat, milk, eggs, livestock, and poultry. Extensive searches were conducted to identify peer-reviewed articles on applications of PFAS in consumer products and the effects of human PFAS exposure on organ toxicity and the circulatory, neural, endocrine, reproductive, and immune systems, metabolism, cancer, and epigenetics. Additional searches were conducted to identify scholarly articles involving PFAS regulations, remediation techniques for contaminated water and soil, and minimizing PFAS recycling and exposure in biosolids, wastewater, anaerobic digesters, compost, and animal manure.

3. What Are PFAS?

Perfluoroalkyl and polyfluoroalkyl substances are a large and diverse group of nearly 15,000 synthetic chemical compounds containing strong carbon–fluoride bonds in the alkyl chains of different lengths [1]. They are often classified as either legacy or emerging, long-chain or short-chain, bioaccumulation potential, water solubility, relative toxicity, and their

polymer composition [5]. Long-chain PFAS consist of perfluoroalkyl carboxylates (PFCAs) that contain eight or more carbons such as perfluorooctanoate (PFOA) and perfluoroalkane sulfonates (PFSAs) that contain six or more carbons such as perfluorooctane sulfonate (PFOS) [17]. Short-chain PFAS include PFCAs that contain seven or fewer carbons such as perfluorohexanoate (PFHxA) and perfluorohexane sulfonate (PFHxS), along with PFSAs that have five or fewer carbons such as perfluorobutanesulfonate (PFBS) [17]. In addition to the many PFCAs and PFSAs, there are many other groups of PFAS compounds [18], and a partial list is shown in Table 2.

Table 2. Partial list of poly- and perfluoroalkyl substances (PFAS) by chemical group classification, compound names, and abbreviations.

PFAS Group/Abbreviation	Compound Name	Abbreviation
Perfluoroalkyl sulphonic acids (PFSAs)	Perfluorobutane sulfonic acid (n = 4)	PFBS
	Perfluoropentane sulfonic acid (n = 5)	PFPeS
	Perfluorohexane sulfonic acid (n = 6)	PFHxS
	Perfluoroheptane sulfonic acid (n = 7)	PFHpS
	Perfluorooctane sulfonic acid (n = 8)	PFOS
	Perfluorononane sulfonic acid (n = 9)	PFNS
	Perfluorodecane sulfonic acid (n = 10)	PFDS
	Perfluorododecane sulfonic acid (n = 12)	PFDoDS
Perfluoroalkyl carboxylic acids (PFCAs)	Trifluoroacetic acid	TFA
	Perfluoropropanoic acid (n = 2)	PFPrA
	Perfluorobutanoic acid (n = 3)	PFBA
	Perfluoropentanoic acid (n = 5)	PFPeA
	Perfluorohexanoic acid (n = 6)	PFHxA
	Perfluoroheptanoic acid (n = 7)	PFHpA
	Perfluorooctanoic acid (n = 8)	PFOA
	Perfluorononanoic acid (n = 9)	PFNA
	Perfluorodecanoic acid (n = 10)	PFDA
	Perfluoroundecanoic acid (n = 11)	PFUnDA
	Perfluorododecanoic acid (n = 12)	PFDoDA
	Perfluorotridecanoic acid (n = 13)	PFTrDA
	Perfluorotetradecanoic acid (n = 14)	PFTeDA
	Perfluorohexadecanoic acid (n = 16)	PFHxDA
	Perfluorooctadecanoic acid (n = 18)	PFODA
Perfluoroalkyl phosphonic acids (PFPAs)	Perfluorohexane phosphonic acid (n = 6)	
	Perfluorooctane phosphonic acid (n = 8)	
	Perfluorodecane phosphonic acid (n = 10)	
Perfluoroalkyl phosphinic acids (PFPiAs)	6:6 Perfluoroalkyl phosphinic acid (m = 6, n = 6)	6:6 PFPiA
	6:8 Perfluoroalkyl phosphinic acid (m = 6, n = 8)	6:8 PFPiA
	8:8 Perfluoroalkyl phosphinic acid (m = 8, n = 8)	8:8 PFPiA
Perfluoroalkane sulphonamides (FASAs)	Perfluorooctane sulphonamide (n = 8)	FOSA
	N-Methyl fluorobutane sulphonamide (n = 4)	MeFBSA
	N-Methyl fluorooctane sulphonamide (n = 8)	MeFOSA
	N-Ethyl fluorooctane sulphonamide (n = 8)	EtFOSA
N-Alkyl perfluoroalkane sulphonamido acetic acids (FASAAs)	Perfluorooctane sulphonamidoacetic acid	FOSAA
	N-Methyl fluorooctane sulphonamido acetic acid	MeFOSAA
	N-Eethyl fluorooctane sulphonamido acetic acid	EtFOSAA
N-Alkyl perfluoroalkane sulphonamido ethanols (FASEs)	2-N-Methyl fluorooctane sulphonamido ethanol	MeFOSE
	2-N-Ethyl fluorooctane sulphonamido ethanol	EtFOSE
Perfluoroalkyl iodides (PFAIs)	Perfluorohexyl iodide (n = 6)	PFHxI
	Perfluorooctyl iodide (n = 8)	PFOI
	Perfluorodecyl iodide (n = 10)	PFDI
Perfluoroether sulphonic acids (PFESAs)	6:2 Chlorinated polyfluorinated ether sulphonic acid (n = 6)	6:2 Cl-PFESA
	8:2 Chlorinated polyfluorinated ether sulphonic acid (n = 8)	8:2 Cl-PFESA
	10:2 Chlorinated polyfluorinated ether sulphonic acid (n = 10)	10:2 Cl-PFESA
Perfluoroether carboxylic acids (PFECAs)	Hexafluoropropylene oxide dimer acid	HFPO-DA
	Hexafluoropropylene oxide trimer acid	HFPO-TA
	4,8-Dioxa-3H-perfluorononanoic acid	ADONA
Perfluorooctane sulphonamido ethanol-based phosphate esters (SAmPAPs)	Phosphate diester of N-ethylperfluorooctane sulphonamido ethanol	SAmPAP diester

Table 2. *Cont.*

PFAS Group/Abbreviation	Compound Name	Abbreviation
	Phosphate triester of N-ethylperfluorooctane sulphonamido ethanol	SAmPAP triester
Cyclic perfluoroalkyl sulphonic acids (cyclic PFSAs)	Perfluoromethylcyclohexane sulphonic acids	PFMeCHS
	Perfluoroethylcyclohexane sulphonic acids	PFECHS
Fluorotelomer sulphonic acids (FTSAs)	n:2 Fluorotelomer sulphonic acids (n = 4, 6, 8, 10)	N:2 FTSA
Fluorotelomer carboxylic acids (FTCAs)	n:2 Fluorotelomer carboxylic acids (n = 6, 8, 10)	n:2 FTCA
	n:3 Fluorotelomer carboxylic acids (n = 5, 7)	n:3 FTCA
Fluorotelomer unsaturated carboxylic acids (FTUCAs)	n:2 Fluorotelomer unsaturated carboxylic acids (n = 6, 8, 10)	n:2 FTUCA
Fluorotelomer olefins (FTOs)	n:2 Fluorotelomer olefins (n = 6, 8, 10)	n:2 FTO
Fluorotelomer alcohols (FTOHs)	n:2 Fluorotelomer alcohols (n = 4, 6, 8, 10, 12)	n:2 FTOH
Fluorotelomer iodides (FTIs)	n:2 Fluorotelomer iodides (n = 4, 6, 8)	n:2 FTI
Fluorotelomer acrylates (FTACs)	n:2 Fluorotelomer acrylates (n = 4, 6, 8, 10, 12)	n:2 FTAC
Fluorotelomer methylacrylates (FTMACs)	n:2 Fluorotelomer methyacrylates (n = 6, 8)	n:2 FTMAC
Polyfluoroalkyl phosphate monoesters (monoPAPs)	n:2 Polyfluoroalkyl phosphate monoesters (n = 4, 6, 8, 10)	n:2 monoPAP
Polyfluoroalkyl phosphate diesters (diPAPs)	n:2 Polyfluoroalkyl phosphate diesters (m = n = 4, 6, 8, 10)	n:2 diPAP
	4:2/n:2 Polyfluoroalkyl phosphate diesters (m = 4, n = 4, 6)	4:2/n:2 diPAP
	6:2/n:2 Polyfluoroalkyl phosphate diesters (m = 6, n = 6, 8, 10, 12, 14)	6:2/n:2 diPAP
	8:2/n:2 Polyfluoroalkyl phosphate diesters (m = 8, n = 8, 10, 12)	8:2/n:2 diPAP
	10:2/10:2 Polyfluoroalkyl phosphate diesters (m = 10, n = 10)	10:2/10:2 diPAP

Identifying and measuring PFAS that are present in relatively low concentrations (parts per trillion; ng/L) in various matrices requires the use of expensive and sophisticated analytical equipment including gas chromatography-mass spectrometry (GC-MS) or high-performance liquid chromatography-tandem mass spectrometry (HPLC-MS/MS) capable of providing repeatable results across laboratories [18]. The most widely studied PFAS is PFOS, which was the initial target compound of concern and was defined as a Persistent Organic Pollutant by the 2011 Stockholm Convention as a target compound requiring monitoring because of its relative abundance, toxicity, and ability to bioaccumulate [19]. However, several other PFSAs and PFCAs, such as PFOA, are also compounds of concern for human health worldwide [6]. Unfortunately, toxicity evaluations have been limited to only a few PFAS compounds, have often been conducted by industry organizations which may not be objective, and are based on standard testing guidelines that do not usually include histopathology and carcinogenesis evaluations [6,20]. Although new shorter chain PFAS have been promoted by chemical companies as being safer and more environmentally sustainable alternatives to legacy long-chain PFAS, due to their reduced bioaccumulation potential and acute toxicity [21], there is increasing evidence from epidemiological and toxicological studies that shows that short-chain PFAS are also associated with increased human health risks including fetal development, neurodevelopment, hepatic and reproductive toxicity, and immunotoxicity similar to those of long-chain PFAS [22–25]. Short-chain PFAS are more mobile than long-chain PFAS in the environment, which makes them highly persistent and contributors to similar toxicity and health risks to long-chain PFAS. As a result of their co-existence and resilience in the environment, and with evidence of similar toxicity and health risks, ongoing risk

assessments suggest that PFAS regulations should involve discontinuation and phasing out of all classes (short-chain and long-chain) PFAS compounds used in food packaging and other products due to safety concerns [26–29].

4. Why Should We Care About PFAS?

There is an overwhelming body of scientific evidence (more than 124 scientific studies) that shows that human exposure to PFAS causes detrimental health effects associated with nearly every organ (liver, kidneys, lungs, heart, brain, bones, and reproduction) and the physiological system (circulatory, neural, endocrine, reproductive, and immune) in the human body (Table 3). The most documented and diverse adverse health effects of PFAS involve brain, neurological and behavioral dysfunction (i.e., Attention Deficit Hyperactivity Disorder, Alzheimer's dementia, reduced IQ, Parkinson's, cerebral palsy, stroke, hand–eye coordination issues, and delayed development of linguistics, behavior, hand–eye coordination), along with endocrine-system disruption, infertility, and reproductive problems (i.e., miscarriage, reduced fetal development, premature births). Human exposure to PFAS has also been associated with kidney, testicular, breast, and liver cancer, and detrimental health effects associated with PFAS have been shown to genetically transfer to subsequent generations (Table 3). The extensive summary shown in Table 3 was compiled to emphasize the large amount of scientific evidence that consistently shows alarming, diverse, and detrimental human health effects experienced in populations around the world. Nearly all previous PFAS reviews provide only a cursory overview of selected health effects from PFAS exposure from a limited number of studies, which may give the impression that PFAS exposure is not the serious public health crisis that it truly is.

Table 3. Summary of toxic effects of PFAS exposure on human health.

Organ or System	Toxic Effects	References
Liver	Nonalcoholic fatty liver disease; liver fibrosis; reduced liver-function data	[30–34]
Kidney	Reduced toxin excretion; chronic kidney disease	[35–39]
Lungs	Promotes asthma in children	[40]
Heart/circulatory system	Cardiovascular problems; hypertension; myocardio infarction and stroke	[41–48]
Brain/nervous system	Attention Deficit Hyperactivity Disorder; Alzheimer's dementia; autism spectrum disorder; brain structure and volume; hearing impairment; reduced IQ; short-term memory loss; Parkinson disease; developmental delay in linguistics, hand–eye coordination, behavior; cerebral palsy; stroke; reduced neurobehavior function, cognition, and neuronal network function	[49–80]
Bones/skeletal system	Osteoporosis; reduced bone health, bone mineral content, and bone density	[42,81–88]
Fertility/reproductive system	Infertility; delayed occurrence of desired pregnancy; miscarriage; lifetime effects on reproductive organs and health; maternal hypertension; preeclampsia; reduced fetal birth weight, fetal growth, fetal head growth; tendency for premature birth; increased mortality; intrauterine disorder of thyroid hormones	[45,47,89–115]
Endocrine system	Thyroid, steroid, and sex-hormone disruption	[116–124]
Metabolism	Disrupted glucose, fat, bile acid, and cholesterol metabolism; type 2-diabetes; gestational diabetes	[110,125–132]
Immune system	Reduced antibody response to vaccines; autoimmune diseases; ulcerative colitis	[133–139]
Cancer	Kidney, testicular, and post-menopause breast cancer; secondary effects of fatty liver, liver cirrhosis leading to liver cancer	[140–148]
Epigenetics	Genetic transfer of PFAS effects to subsequent generations	[149–154]

Direct human exposure to PFAS occurs by inhalation of air particles, consumption of contaminated food and drinking water, and physical skin contact [155–158]. A study conducted in China showed that indoor dust and drinking water represented <9% of PFAS exposure in humans, which is much less than the consumption of contaminated food [159]. However, in the Eastern United States, 60% of the public water supply and 20% of domestic wells contained at least one detectable type of PFAS [160]. Results from another study

estimated that about 45% of drinking-water samples from unregulated private wells and regulated public supplies of tapwater in the U.S. contain at least one type of PFAS [161]. Results from these studies exemplify the widespread contamination of PFAS in drinking water, which is an essential resource for life.

Food is a primary route of human exposure to PFAS, especially contaminated animal-derived foods [162]. Unfortunately, the likelihood of human exposure to PFAS is difficult to control because of differences in the prevalence of contamination among geographic regions, along with age, eating habits, lifestyle, and ethnicity which can be highly variable [162]. Food contamination with PFAS also occurs from fast-food packaging, microwave popcorn bags, and high-temperature cooking practices such as frying [163]. Public monitoring of beverages, processed meats, and food-packaging containers is needed to identify PFAS-contaminated sources and decrease exposure in the general population [164]. People can also be exposed to PFAS by working in occupations such as firefighting, in chemicals manufacturing facilities, and using a variety of products and packaging materials made with PFAS.

The widespread contamination of PFAS in the environment, drinking water, and food supply and the extensive adverse health effects of human exposure has led to an urgent need for stricter regulations on the production and use of PFAS in consumer products to reduce contamination in food and drinking water. However, unlike other chemical hazards that are monitored as part of routine food-safety programs in many countries, there is no standardized international food safety monitoring system for PFAS. Effective regulatory frameworks for PFAS need to be established using standardized, internationally accepted guidelines for the analysis of PFAS in human serum, plasma, and urine samples to support risk assessments and identification of high-risk environments [165,166]. Most of the limited advisory guidelines for PFAS exposure from food and drinking water were established nearly 20 years ago when our knowledge about the adverse health effects of PFAS was very limited and included only PFOA and PFOS compounds [167]. Although these guidelines are often used to compare analyzed concentrations in food and drinking water with estimated "safe" daily or weekly consumption limits, they vary considerably based on the type of measure (i.e., tolerable daily or weekly intake, health advisory level, reference dose) and maximum tolerable PFOA, PFOS, perfluorobutanesulfonic acid (PFBS), or total PFAS intake due to differences in age, gender, and those living in urban versus rural environments [162,167]. Because of different total daily PFAA intake and the relative contributions from different foods for different age groups, different approaches are needed to develop policies to control human exposure for different age groups. Therefore, until more information on toxicology, amounts of daily intake, and effects of long-term exposure of more types of PFAS compounds in food and drinking water is available, and a standardized testing and monitoring system for PFAS is developed for government regulated food safety programs, it will be difficult to minimize human exposure to these hazardous PFAS chemicals. In the meantime, altering consumer behavior by avoiding high-risk consumer products can minimize PFAS exposure and the likelihood of experiencing associated adverse health effects (Table 4). However, because of the pervasiveness and resilience of PFAS in the environment, we also need to understand other sources of environmental contamination and exposure beginning with the air that we breathe.

Table 4. Consumer practices that can reduce PFAS exposure.

Consumer Product	Action
Drinking water	Test drinking water supplies to monitor presence and concentrations of PFAS Request water provider to install effective treatments to remove PFAS Install in-home reverse osmosis or granulated active carbon filters to effectively remove PFAS Boiling is ineffective and actually increases PFAS concentrations if contaminated
Food	Replace non-stick cookware with stainless steel, glass, or ceramic alternatives
	Avoid heating food packaged in grease-resistant packaging and containers from fast-food restaurants and pizza boxes Do not consume microwave popcorn in PFAS-treated microwave bags
Household Personal care	Do not use furniture, upholstery, rugs, carpets, and bedding that are water- or stain-resistant Consider eliminating or minimizing use of cosmetics, makeup, nail polish, shampoo, dental floss, and lotions

5. PFAS in the Atmosphere

Various forms of PFAS are found in the atmosphere. Gaseous PFAS are comprised of volatile forms (FTOHs, FOSAs, FOSEs, FTACs) that have relatively low vapor pressure and higher boiling points which enable them to easily evaporate; short-chain PFAS (PFHpA, PFBS, PFBA) and secondary FTOHs formed during biotransformation of fluorotelomer-based compounds. Particulate PFAS (PFOA and PFOS) have low volatility but can adsorb to atmospheric particulate matter and be transported by air; long-chain PFAS have a greater tendency to bind to airborne particles, and ultrafine particles attract PFOA, PFNA, and PFDA. Atmospheric PFAS emissions have been detected throughout the world [168–170], including volatile PFAS precursors in remote regions resulting from long-range atmospheric transport of ionic forms by marine aerosols [171,172] and by air-sea exchange [173]. Airborne dust particles can adsorb and transport PFAS long distances [18]. Furthermore, volatilization of PFAS from product manufacturing, wastewater treatment facilities, and landfills [174,175] results in very high atmospheric concentrations, while deterioration of functional textiles and elevated summer temperatures also contribute to air PFAS emissions [176–179]. Air contaminated with PFAS can accumulate on plant leaves and grasses and can subsequently be consumed by livestock [14,180,181]. Animal and human exposure to PFAS can also occur by inhaling contaminated air and dust and contact exposure to skin and feathers [182–185]. Unfortunately, there are no effective technologies to remove PFAS from contaminated air, and more research is needed to understand the transport and fate of PFAS in the atmosphere to develop practical and cost-effective technologies for PFAS removal. Although PFAS may be present in air, the concentrations are much lower than those found in contaminated water and soil.

6. PFAS in Water

Natural water sources such as rivers, lakes, oceans, rain, and snow have all been shown to be contaminated with PFAS around the world. Most perfluoroalkyl acids have relatively high solubility in water which makes them quite mobile in the environment [186,187]. Water contamination of PFAS occurs from atmospheric precipitation [188], and close proximity to industrial manufacturing sites, commercial applications, and firefighting activities [189]. Because PFAS can be adsorbed on suspended particles [190], they can easily migrate to surface water and increase sediment concentrations [191]. Various PFAS have also been shown to be associated with microplastics in lake environments where sorption onto microplastics is increased in the presence of organic matter [192]. Aquatic organisms, such as fish, directly absorb PFAS through skin and gills, and indirectly through PFAS-contaminated food consumed in their digestive systems [193]. As a result, PFAS accumulate

in fish and other aquatic foods which become a major source of human exposure through their consumption [194,195].

Maintaining high-quality irrigation and drainage water is essential to support ecosystem and human health in agricultural regions [196]. However, irrigation water contaminated with PFAS has been identified as a more important source of PFAS contamination in plants than the use of PFAS-contaminated biosolids as a soil amendment [13,167] because the mobility and bioavailability of PFAS is greater in irrigation water [197] due to the use of recycled water in locations with water shortages [198]. Very little research has been conducted to determine the prevalence and concentrations of PFAS in major agricultural regions (e.g., Iowa) in the U.S., but results from a recent survey showed that at least one PFAS was detected in 32% of streams sampled in Iowa, and 10 different types of PFAS were found in various streams across the entire state [199].

Wastewater-treatment facilities are used to purify water for drinking and other domestic purposes, but the conventional water-treatment methods used are generally ineffective for PFAS removal [200,201], and often result in PFAS concentrations exceeding human-health advisory limits [200,202,203]. Consequently, tap water contaminated with PFAS and used for cooking and food processing, such as making coffee and cola beverages, can be a major source of human exposure [204]. A summary of technologies that have been evaluated for removing PFAS contaminants in drinking water is shown in Table 5. Advanced filtration using reverse osmosis and nanofiltration are energy-efficient processes that are effective for separating and concentrating PFAS for subsequent disposal or treatment, but some of these techniques may be expensive. However, these removal technologies concentrate PFAS and require careful consideration of post-treatment management and disposal. Furthermore, the large-scale practical application and cost-effectiveness of most of these technologies are major limiting factors preventing their widespread use.

Table 5. Summary of technologies for removing PFAS from contaminated water.

Technology	Brief Description	References
Adsorption processes	Adsorption using single-use and renewable ion-exchange resins that transfers a wide variety of PFAS compounds and concentrations from the aqueous phase to a solid matrix with high selectivity and efficiency; adsorption using granular activated carbon is the most commonly used method, but active carbon must be regenerated frequently	[8,205–213]
Filtration processes	Advanced filtration using reverse osmosis and nanofiltration are energy-efficient processes that force pressurized water streams through a semi-permeable polymer membrane to separate and concentrate PFAS for subsequent disposal or treatment, but cost of some techniques may limit practical application	[8,208,214–217]
Electrochemical oxidation	Practical application under development and involves using ozone, ammonium persulfate, or hydrogen peroxide/Fenton reagent	[218–220]
Plasma treatment	Practical application under development and involves using high-voltage electrical discharges to generate free radical species	[221]
Sonolysis	Practical application under development and involves using high-frequency ultrasound to cause mineralization	[222]
Foam fractionation	Practical application under development and involves sequestering PFAS into air or ozone bubbles in the air–water interface	[223]

7. PFAS in Soil

Soil is a global reservoir and long-term source of PFAS contamination because its organic matter serves as a sink to collect and store PFAS originating from industrial sources and provides a route in which to transfer PFAS to rivers, lakes, surface water, and groundwa-

ter [224]. Soil structure plays an important role in the chemical and physical transformation of PFAS and movement within and between environmental matrices [9]. However, it is important to recognize that the relative impacts of PFAS in soil depends on interactions between many soil types, land uses, and types of PFAS (i.e., long-chain versus short-chain). Soil absorbs PFAS from the atmosphere and water at different rates depending on soil type and the extent of contaminated irrigation water use [225,226]. The persistence of PFAS in soils involves its ability to partition in the soil matrix [16], and the proteins present in soil organic matter provide a sorption site and reservoir for PFAS [227]. Soils with high amounts of total organic carbon, iron oxide, and aluminum oxide concentrations have greater relative adsorption of PFAS, and long-chain PFAS compounds appear to adsorb to soil more readily than short-chain compounds [225]. Once soil is contaminated with PFAS, the solubility of these forever chemicals enables them to be transported to surface water or leach into groundwater, leading to bioaccumulation in plants and animals and creating a circular exposure pathway [228]. The movement of PFAS in the environment and its subsequent bioaccumulation and toxicity is dependent on carbon-chain length and chemical characteristics (solubility, bioavailability), along with soil texture, enzymes, and fertilization conditions [189]. Soils contaminated with PFAS adversely affect soil function, threaten drinking-water safety, and lead to contaminated plant- and animal-derived foods that cause many detrimental human-health effects [189]. In general, PFAS contamination in soils from the application of aqueous film-forming foam (a type of foam used by fire departments to fight fires started by oil, gasoline, or other flammable liquids) is more severe than contaminated soils from fluorochemical manufacturing and biosolids from sewage-treatment facilities, landfills, and irrigation [189]. Several technologies have been developed for removing or destroying PFAS in soil and are summarized in Table 6. However, most of these methods are extremely expensive, disruptive to land being treated, and are associated with risks of chemical contamination. Of these various approaches, ball milling is an energy-efficient and cost-effective method for removing PFAS from contaminated soil, but there is considerable interest and potential for using bioremediation processes involving specific bacteria, fungi, and plant species to acquire, transform, degrade, and stabilize PFAS in contaminated soil.

Table 6. Summary of technologies for removing or destroying PFAS in contaminated soil.

Technology	Brief Description	References
PFAS removal		
Immobilization	Addition of modified clay or activated carbon or stabilization agents such as Portland cement to soil to absorb PFAS or create an impermeable layer to limit movement to groundwater supplies	[229–231]
Soil washing	Requires excavation of soil, removal of largest particles, and treatment of remaining fine particles with an extracting agent	[232]
Soil flushing	Involves injection and recovery of extraction fluid without removal of soil from the site	[233]
Water solubilization, organic solvents, chelating agents, acids, and surfactants	Water-soluble PFAS can be removed by water solubilization while other higher hydrophobicity PFAS require organic solvents, chelating agents, acids or surfactants	[229,234–237]
PFAS destruction		
Thermal destruction	Energy-intensive and expensive process involving heating at 350 to 900 °C to cause PFAS desorption from soil and forming a gas stream which is further heated at >1200 °C to break down PFAS and retain fluoride ions in a molecular scrubber	[229,238,239]

Table 6. *Cont.*

Technology	Brief Description	References
Chemical reduction/oxidation	Involves the addition of highly reactive chemicals, such as heat- or iron-activated persulfate, by vertical injection wells in upstream contaminated soil and extraction wells downstream to protect groundwater; reductive processes involving ultraviolet-light-generated solvated electrons that cause defluorination without the use of chemicals	[219,240–246]
Ball milling	An energy- and cost-effective method for removing PFAS from contaminated soil by processing through specific reactors and being forced to collide with solid balls that cause chemical transformations and physical grinding	[247,248]
Bioremediation	Utilizes specific bacteria and fungi or plant species that transform, degrade, acquire, and stabilize PFAS	[225,249–255]

8. PFAS in Plants and Plant-Derived Foods

Plants become contaminated with PFAS through exposure to contaminated air, water, and soil. Irrigation water and biosolids from sewage sludge applied to agricultural land are the most problematic because of their high PFAS concentrations [10,12,13], but other localized hotspots such as effluents from wastewater treatment plants, industrial purification facilities, landfills, and areas treated with firefighting foams are specific areas where PFAS are concentrated and bioaccumulate, and should be avoided to break their recurring circulation in the environment. Several factors contribute to PFAS bioavailability, bioaccumulation, and phytotoxicity in plants including soil organic carbon, cation exchange capacity, temperature, salinity, pH, and the presence of earthworms [256–260].

A limited number of studies have been conducted to collect samples of various types and parts of plants, fruit and vegetables, and tubers produced under various conditions and regions around the world and to determine concentrations and the extent of PFAS bioaccumulation [261–272]. The results from these studies showed that PFAS distribution varies across roots, stems, leaves, fruits, and heads, and among species. For example, carrots accumulate greater amounts of PFAS than potatoes and cucumbers because they absorb water and nutrients for the entire plant compared with potatoes, which are primarily storage tubers, and cucumbers, which are fruits. Shoots appear to be the main parts of plants that accumulate PFAS compared to edible portions. For lettuce, radishes, celery, tomato, and pea plants, some types of PFAS were found to have increasing concentrations from roots to above-ground edible parts, while lower concentrations of other types of PFAS (PFOA and PFOS) were found in above-ground parts of the plants. Vegetables grown on soils contaminated with sewage sludge contain relatively high concentrations of PFAS compared with those grown on uncontaminated soils, but the extent of bioaccumulation depends on the type of biosolids from sewage sludge and anaerobic digestates applied to soils [13]. Likewise, concentrations of PFAS in fruits vary by species and origin and are generally greater in concentrations than those found in other plant-based food groups such as cereals [270].

A comprehensive review of studies evaluating the source, bioaccumulation, and food-safety risk assessments of PFAS in vegetables indicated that they can contain significant concentrations of PFOA, PFOS, and some short-chain PFAS primarily derived from atmospheric deposition, grown on biosolids amended soil, and from using contaminated irrigation water [167]. Geographic location and proximity to point source PFAS production is a major determining factor for the likelihood of consuming foods exceeding advisory PFAS dietary intake guidelines. Although the prevalence and concentrations of PFAS vary among different types of vegetables, dietary-exposure risk assessments for PFAS uptake based on current guidelines for human exposure have generally been reported to be below current human-health toxicity reference values for most plant-based foods in many countries [167,265,273–275]. However, this conclusion may underestimate the long-term health

risks due to limited data, synergistic and interactive effects of exposure to complex PFAS mixtures, and insufficient understanding of chronic low-dose dietary exposure, especially for sensitive populations. Furthermore, these evaluations were based on using different analytical methods for measuring a limited number of PFAS compounds and calculating human consumption based on limited toxicity guidelines. Other studies have shown that growing vegetables at homes near a fluorochemical industrial park [276], and vegetables grown using irrigation water containing PFOA and PFOS concentrations below the U.S. EPA lifetime health advisory for drinking water, may not be adequate to protect exposure to vegetables [277]. Furthermore, models have shown that using real-world concentrations of PFAS in contaminated ground water to irrigate vegetable production on farms would result in exceeding current human-health toxicity reference values [277].

Similar to vegetables and fruits, a limited number of studies have been conducted to assess the PFAS concentrations in cereal grains (maize, oats, wheat, canola, and perennial ryegrass) and associated plant compartments including straw, leaves, roots, husks, and stover [261,266,272,278–284]. In general, there are large differences in PFAS concentrations among plant species, but greater accumulation occurs in the vegetative portions of plants, especially straw, compared with grains, and PFAS concentrations increase with increasing concentrations of PFAS in soils. Several factors affect the uptake of PFAS in cereals including soil PFAS concentration and organic matter, the surface area of root systems, the amount of biomass accumulation, the amount of water transpired, irradiance, temperature, humidity, and PFAS chain length.

Soybeans are the most important oilseed crop worldwide and the fourth most abundant cultivated crop after wheat, corn, and rice [285]. Studies have shown that applying biosolids contaminated with PFAS to soil used to grow soybeans resulted in significant uptake of PFOA and PFOS in soybeans [283]. Uptake of perfluorooctane sulfonamide readily occurs in soybean plants where it is metabolized to other PFAS forms and activates their antioxidant defense system [286]. Jiang et al. [287] studied the effects of a PFAS mixture on the soil–microbe–soybean plant system and showed significant effects on the abundance of nitrification and denitrification genes in microbial communities in soil, rhizomes, and root nodules which alter the nitrogen cycle in soil and may require nitrogen fertilization to maximize soybean yields. The effects of PFAS on altering microbial communities in soil and plants that lead to changes in the nitrogen cycle is an example of the type of complex interactions between PFAS and the environment that are poorly understood and require extensive investigation.

Integrated crop and livestock systems are essential for a sustainable, circular, One Health agri-food system because of the complementary effects of practices that improve soil health, reduce pathogens, pests, and weeds, and recycle nutrients (i.e., animal manure) to minimize nutrient losses from the system [9]. As we transition toward a more circular bioeconomy, the amplifying effects of PFAS throughout the food chain is a major One Health concern. Contamination levels of PFAS in the atmosphere, groundwater, and soil become more concentrated in pastures and forages, major cereal and oilseed crops and their co-products used in animal feeds, and crop residues (e.g., straw and stover) used as animal bedding materials, which further bioaccumulate and concentrate in food-producing animals where PFAS are concentrated in meat, milk, and eggs to ultimately cause adverse effects on human health when consuming these animal-derived foods. Furthermore, in a circular bioeconomy, manure excreted from animals consuming PFAS in feed and drinking water is applied to cropland which further promotes continuing cycling of PFAS and its detrimental health effects on ecosystems and food production. Therefore, one of the unintended detrimental consequences of circular agri-food systems is perpetuating PFAS

contamination. This important aspect needs to be addressed as a key component of global-health risk-management strategies.

9. PFAS in Food-Producing Animals and Animal-Derived Foods

Animal-derived foods including fish, seafood, meat, milk, and eggs are one of the main routes of human exposure to PFAS [162,288,289]. In fact, results from a few large sampling surveys that determined the presence and concentrations of selected PFAS compounds in a wide variety of foods showed that fish and seafood had the greatest amount of PFAS in all countries, but the concentrations detected did not exceed current standards for the maximum tolerable daily intake [273,274,290–292]. The results from some studies have shown that some samples of meat, milk, and eggs contain PFAS concentrations comparable to fish and seafood, and that animal-derived foods generally contain greater concentrations of PFAS than foods of non-animal origin [273,293]. However, the accurate quantification of various PFAS compounds in these food matrices is often a major analytical challenge because of their chemical complexity, relatively low PFAS concentrations, and environmental contamination of blanks, laboratory materials, and equipment [294].

Livestock and poultry play an essential role in a circular food system by recycling plant-based nutrients in biomass and agri-industrial by-products into valuable, nutrient-dense food products and manure, which reduces the environmental burden that would have been associated with their disposal if these materials had not been diverted toward productive use in animal feed [295]. The PFAS in contaminated soil, water, and plant-based feedstuffs have a substantial direct effect on PFAS exposure and bioaccumulation in food-producing animals and their subsequent production of meat, milk, and eggs. In addition, in many parts of the world, feed crops and associated by-products and co-products are produced in one geographic region and fed to livestock and poultry in another region of the global economy and agri-food system [296]. This decoupling of local feed production with livestock production not only disrupts nutrient cycles by depleting resources (land, water, nutrients) in feed production regions and accumulating nutrient resources (manure) in livestock production regions, but it also facilitates the transfer of PFAS from one geographic region to another. Therefore, there are substantial benefits in recoupling livestock and feed production at the local level, especially in areas with low environmental PFAS contamination, to prevent the perpetual recycling of PFAS through feed ingredients in global circular agri-food systems.

Although livestock and poultry play an essential role and provide important benefits in a circular agri-food system, they also contribute to unintended consequences by serving as a key recycler and bioaccumulator of PFAS, resulting in the production of contaminated meat, milk, and eggs, which are a main source of human PFAS exposure. Livestock and poultry can be directly exposed to PFAS from contaminated air, water, soil, and consumption of crop biomass grown on contaminated soil. Several studies have shown that the main exposure pathways to PFAS are from consuming contaminated feed and drinking water [297–303]. Models have estimated that 78% of ruminant exposure to PFAS is from the consumption of forages, and more than 80% of PFAS in poultry and pigs raised in outdoor production systems is from soil contamination [19]. Furthermore, the use of contaminated recycled materials (i.e., wood shavings, shredded cardboard, dried paper pulp, poultry litter ash, meat and bone meal ash) for livestock and poultry bedding can also be a major source of PFAS exposure [304,305]. When food-producing animals are exposed to contaminated recycled materials, the short- and long-chain compounds accumulate at different rates in different tissues that may not only lead to adverse health and reproductive effects in animals, but are also transferred into meat, milk, and eggs for human consumption.

In general, the distribution of PFAS in body organs and tissues is similar among species, with the main differences associated with PFAS chain length, dose, and sex [14]. Liver and blood contain the greatest concentrations of PFAS among various body tissues and organs, but the proportion varies between animal species [14]. Concentrations of PFAS in kidney are generally less than in the blood and liver, while concentrations in muscles are consistently less than those in liver, blood, offal, and kidney across animal species [14]. Although PFAS elimination rates appear to be longer in pigs than most animals, cattle studies have shown wide variation in PFAS elimination rates due to chemical form, dose, age, and sex [14]. Poultry appear to have the fastest rate of PFAS elimination among farm animals, and PFOS has been shown to be the predominant PFAS transferred to egg yolk [306]. In contrast, although studies have shown that PFAS is transferred to cow and sheep milk, it is not preferentially secreted or concentrated in milk [14]. However, despite the ability of animals to bioaccumulate PFAS after the consumption of contaminated feed and drinking water, detrimental health effects from PFAS exposure in livestock and poultry have not been reported. This lack of observed adverse health effects may be due to several factors including the relatively short productive life span (i.e., 6 weeks for broilers, 6 months for pigs, 2 years for cattle) of animals before slaughter; lack of detailed metabolomics, microbiome, immunology, gastrointestinal physiology, and epigenetics evaluations; limited sample size; and differences in relative toxicity and doses of specific PFAS compounds.

Most of the studies conducted to evaluate PFAS bioaccumulation in body tissues and organs, metabolism, excretion, and deposition in meat, milk, and eggs have involved only a few animals that were administered PFAS during a relatively short period of time (Table 7), which likely resulted in a lack of detrimental animal health effects being reported [14]. Only a few studies have evaluated naturally contaminated feed, water, and environmental conditions on PFAS concentrations in meat [307–309], milk [297,299,310,311], and eggs [312–315]. These surveys provide more realistic assessments of real-world, longer-term PFAS exposure of livestock and poultry, and the extent of transfer into animal-derived food products. As a result, models have been developed to estimate the transfer of PFAS from feed, water, and the environment to animal-derived food products while also providing a basis for seasonal cattle and sheep-grazing management strategies to reduce exposure [316–318]. Furthermore, some analytical methods that use key biomarkers for specific chemical forms of PFAS have been developed for detection in meat [319] and milk [320]. However, depending on the specific PFAS compound and the maximum tolerable PFAS limit guidelines for a specific country, some studies have suggested that the concentrations of PFAS in some animal-derived food products are human-health concerns, while other types of PFAS and concentrations detected indicate consumption below threshold levels of concern. However, as previously mentioned, current standards or threshold levels of concern may underestimate the long-term health risks due to limited data, synergistic and interactive effects of exposure to complex PFAS mixtures, and insufficient understanding of chronic low-dose dietary exposure, especially for sensitive populations. Because of these inconsistencies and deficiencies in current standards, it is essential to harmonize the maximum tolerable food-safety standards globally to provide clear guidance.

Table 7. Summary of the effects of PFAS exposure in livestock and poultry on body tissue and organ bioaccumulation, metabolism, excretion, and deposition in meat, milk, and eggs.

Species	PFAS Effects	References
Beef cattle	Single oral dose of PFOA is completely absorbed and excreted in feces and urine within 9 days of dosing but oral doses of PFOS persist in blood, adipose tissue, muscle, liver, bone, and kidney with half-lives of 36 to 385 days depending on tissue; total PFAA concentration in beef liver samples collected in various regions in China were 60-fold greater than in muscle samples but were deemed far below threshold for human-health risks; complex dynamics of PFOS plasma depletion rate indicates withdrawal times depends on initial concentrations and threshold level of concern; PFOS and PFHxS concentrations in drinking water are positively correlated with serum concentrations, and meat from cattle grazing on PFAS-contaminated sites may exceed human health consumption guidelines in some countries; models using serum and tissue estimates from daily cattle exposure to PFAS-contaminated water, pasture, soil and accounting for animal growth, seasonal variability, and differences in concentrations across paddocks have been developed to evaluate exposure-management scenarios	[307,316,317,319,321–323]
Dairy cattle	Exposure to naturally contaminated feed and water resulted in detection of PFOS and PFAAs in liver, blood, and muscle of dairy cows and these compounds have high potential for transfer to milk and meat; various PFAS have different uptake and depuration kinetics which also vary among tissues and extent of secretion in milk; physiologically based pharmacokinetic model shows that although nearly all PFOS consumed is secreted in cow's milk, the half-life was 56 days, indicating a slow elimination rate before producing milk without PFOS; high concentrations of PFOS in calf fetal livers suggest placental-barrier transfer from dam; skin samples could be used for monitoring PFAS in cattle when on-farm blood collection is not possible; multiparous cows with no known exposure to PFAS had higher prevalence of contamination in all milk fractions.	[297–299,301,316,317,324,325]
Sheep and goats	Plasma concentrations, excretion via urine and feces, and secretion in milk were less for PFOA than PFOS-fed contaminated corn silage for 21 days; bioaccumulation of PFAS is positively correlated with intake of contaminated water which varies by season and climate; feeding contaminated grass for up to 112 days increased liver PFOS concentrations, which decreased during depuration, resulting in livers not exceeding EFSA food safety standards	[302,316,326,327]
Swine	Bioaccumulation in plasma (up to 51%), adipose tissue and muscle (40 to 49%), liver, kidney, ovary, and follicular fluid; longer chain lengths increase accumulation; PFAS disrupts redox status, steroidogenesis, and antioxidant defense in granulosa cells in ovary; heat stress alters PFAS distribution that is detrimental to reproduction; pigs have longer PFAS elimination half-lives than most species except humans	[308,328–333]
Broiler chickens	Environmentally relevant concentrations of some forms of PFAS may adversely affect embryonic development (lower heart rate and enlarged liver) due to different toxicity thresholds; injection of increasing doses of PFOS in egg air cells prior to incubation reduced hatchability and increased liver concentrations; three-week oral gavage of 1 mg/kg body weight of PFAS mixture three times weekly had no adverse effects on body or organ weights; liver and kidney are major PFAS accumulation organs and rates of elimination vary between PFOA and PFOS; subcutaneous implantation for 4 wks followed by depuration for 4 wks resulted in no effects on body index, clinical biochemistry, or histology	[308,334–337]
Laying hens	Transfer rates, bioaccumulation, and half-lives of PFAS from feed to eggs varied among PFAS types; drinking water containing increasing concentrations of 4 types of PFAS compounds increased PFAS concentrations in eggs but were below Australia and New Zealand food-safety thresholds; yolks from home-produced eggs contained greater concentrations of long-chain PFASs (i.e., PFOS) than organic, battery, and free-range eggs collected from supermarkets in Netherland and Greece but would not exceed EFSA food safety standards; eggs from backyard chickens in Italy contained PFAS concentrations that would contribute up to 29% of the tolerable weekly intake limit for children; eight types of PFAS were detected in home-grown eggs from free-range hens within a 10 km radius of a fluorochemical plant in Belgium where concentrations of PFOS and PFOA were affected by diet and age of hens, and consumption of two eggs per week would exceed European health guidelines in more than 67% of locations; eggs from organic production had greatest concentrations of PFAS followed by eggs from free-range and cage hens in Poland, but corresponded to 0 to 15% of tolerable weekly intake of adults and 0 to 5% for children; toxicokinetic factors have been identified that influence the different bioaccumulation rates, tissue distribution, and maternal transfer of PFCAs to eggs	[306,312–315,338,339]

Although animal-feed ingredients are a major source of PFAS exposure for livestock and poultry, very few studies have been conducted to evaluate the presence and concentration of various types of PFAS contaminants in common ingredients. The analysis of 18 different animal feeds containing mixtures of plant- and animal-based ingredients for various species (amphibian, fish, invertebrate, and mammal) showed that (1) PFOS, PFHxS, PFOA, and short-chain PFCAs were in the highest concentrations and were the most frequent forms found in all feeds, (2) different ingredients had different PFAS profiles, and (3) plant-based ingredients contained mainly short-chain PFSAs, while animal-based ingredients contained longer-chain PFSAs [340]. Based on these results, PFAS contamination in lab and experimental animal feed can cause numerous potential challenges for interpreting results from PFAS toxicology studies because of (1) the unintended introduction of PFAS during animal-exposure experiments that can lead to premature toxicity and misinterpretation of results, (2) multiple PFAS that may be present in contaminated feeds that can interfere with measuring responses from the target PFAS of interest, (3) contaminated

controls that can make it difficult to interpret PFAS exposure results, and (4) difficulties in evaluating low and environmentally relevant PFAS doses [340].

Feeding rendered animal by-products to food-producing animals is another essential part of recycling nutrients from food waste in a circular bioeconomy and food system [341]. Several types of protein meals, including blood meal, meat and bone meal, meat meal, poultry by-product meal, poultry meal, hydrolyzed feather meal, and fish meal, are sources of high concentrations of highly digestible protein and amino acids that are used in pet food, poultry, livestock, fish, and crustacean diets [341]. In addition, animal fats such as beef tallow, choice white grease, and poultry fats are also recycled as high-energy feed ingredients in livestock and poultry diets. These animal-derived feed ingredients are susceptible to PFAS contamination because they are derived from livestock and poultry tissues that bioaccumulate these compounds. Unfortunately, little is known about the prevalence of contamination, specific types of compounds, and concentrations of PFAS in rendered animal by-products because there is no feed safety-monitoring system designated to analyze these materials, and very few studies have been conducted to gain insights into the prevalence and potential significance of PFAS contamination in these by-products. The results from one study showed that although PFAS concentrations ranged from undetectable to 37 ng/g dry matter, blood meal contained the greatest PFAS concentrations compared with meat meal and feather meal [300]. Furthermore, the total average PFAS concentrations in these animal-derived by-products was about 10 times greater (10.9 ng/g dry matter) than the average total PFAS concentrations (0.75 ng/g dry matter) in plant-derived high-protein ingredients (soybean meal and dried distillers grains with solubles) [300]. These results indicate that rendered animal protein meals appear to be a substantial potential source of PFAS consumption if included in diets for food-producing animals.

Globally, countries in the European Union have been the most proactive in establishing food and animal-feed safety guidelines for PFAS. In 2018, the European Commission assigned the task of developing analytical methods and measures to quantify low concentrations of PFAS compounds using routine analysis in food laboratories to the Reference Laboratory for Halogenated POPs (Persistent Organic Pollutants) in Feed and Food for the purpose of protecting human health from the detrimental effects of PFAS consumption from food [342]. The resulting guidance document was intended to establish analytical parameters to standardize the PFAS analysis of food and feed that would enable (1) establishing maximum concentrations of PFAS in food and feed, (2) establishing databases to recommend actions levels, (3) assessing exposure of populations based on dietary intake and risk, and (4) enforcing regulations once limits were established.

More recently, the EU Commission adopted Regulation 2023/915 in April 2023 which established the maximum tolerable concentrations of four individual and total PFAS (PFOS, PFOA, perfluorononanoic acid—PFNA, PFHxS) in animal feed ingredients (Table 8) and food of animal origin, except milk (Table 9) [343]. These maximum tolerance levels vary because each PFAS has different toxicity kinetics in different animal species, and some estimates have not been determined because of insufficient data. Limited studies have been conducted to analyze samples of blood and liver from farm animals exposed to PFAS in various countries under various conditions of real-world PFAS exposure. For example, blood and livers from farm animals in various regions of Japan were collected and analyzed to show that PFOS was the most common PFAS contaminant and that serum concentrations were greatest in chickens (5.8 ng/mL) followed by cattle (3.0 ng/mL), goats (2.4 ng/mL), horses (0.71 ng/mL), and pigs (0.37 ng/mL), which had lower concentrations than those reported in other studies for wild animals and fish [324]. Similarly, a survey of tissue samples from pigs and chickens raised on farms near Beijing, China [308] had concentrations (wet weight) of total perfluorinated compounds of 3.4 ng/g in pig liver, 0.51 ng/g in pig kidney,

and 0.17 ng/g in pig heart, with lesser amounts found in chicken liver (0.10 ng/g), chicken heart (0.05 ng/g), pork loin (0.02 ng/g), and chicken breast (0.01 ng/g). As a result of the lack of these types of studies, different toxicokinetics among types of PFAS compounds, different PFAS metabolism among animal species, and different rates of bioaccumulation in various organs and tissues, it has been difficult to establish harmonized maximum tolerable standards for PFAS in feed and animal-derived foods. Therefore, although maximum tolerance levels have been established, enacting regulations for PFAS in feed in the European Union is not anticipated in the foreseeable future due to insufficient data to estimate the PFAS concentrations in individual ingredients, and the relative contributions of PFAS-contaminated ingredients to the total diet that would ensure that maximum tolerable levels in animal-derived foods are not exceeded [343]. A PFAS assessment and monitoring system needs to be established to collect and analyze various feed ingredients from different sources and geographic origins to establish a reference database. Until this occurs, the recommended maximum tolerable levels of PFAS in complete feed as shown in Table 8 are the current best estimates to avoid exceeding PFAS in animal-derived foods.

Table 8. Estimated maximum possible PFAS concentrations in complete feeds for feeding laying hens, finishing cattle, sheep, and finishing pigs to avoid exceeding maximum concentrations in foods of animal origin based on EU Regulation 2023/915 (adapted from [343]).

Complete Feed	PFOS	PFOA	PFNA	PFHxS
		μg/kg dry matter		
Laying hens	0.42	0.25	0.29	0.17
Finishing cattle	0.14	NA *	NA	1.0
Sheep	0.21	NA	NA	NA
Finishing pigs	0.07	0.05	NA	0.06
Dairy cows	0.07	6.5	NA	3.7

* NA = not available due to insufficient data.

Table 9. Maximum recommended PFAS concentrations in foods of animal origin based on EU Regulation 2023/915 (adapted from [343]).

Food	PFOS	PFOA	PFNA	PFHxS
		μg/kg fresh weight		
Eggs	1.0	0.30	0.70	0.30
Meat from cattle, pigs, and poultry	0.30	0.80	0.20	0.20
Meat from sheep	1.0	0.20	0.20	0.20
Offal from cattle, sheep, pigs, and poultry	6.0	0.70	0.40	0.50
Milk from cattle *	0.02	0.01	0.05	0.06

* Indicative concentrations based on EU Recommendation 2022/1431.

10. PFAS in Animal Manure, Food Waste, Compost, and Anaerobic Digestates

Animal manure and food waste are another poorly understood aspect of the detrimental environmental effects of PFAS contamination, but they play a very important role in perpetuating the recycling of PFAS in circular agri-food systems. As previously described, numerous plant- and animal-derived food sources have been shown to be contaminated with multiple PFAS compounds. This is important because 33 to 40% of the food that is produced globally is lost or wasted annually [344]. Unfortunately, most food loss and

waste is disposed in landfills, which is not only a major contributor to the production of methane and carbon dioxide emissions resulting from decomposition, but it also enables PFAS accumulation [345]. Results from a recent study showed that food-contact materials present in food waste were the primary source of 21 different PFAS compounds detected in food waste disposed in landfills, the amount of PFAS in incinerator plant leachate was greater than leachate from landfills, and many PFAS forms had the ability to leach into water [346].

Because of the environmentally damaging effects of disposing of food waste in landfills, attempts are being made to divert food waste from landfills and toward aerobic composting to produce soil amendments, anaerobic digestion to produce biogas, and recycling energy and nutrients into animal feed [345]. Although there are limited data, food-waste streams are a source of PFAS in compost and digestates because these compounds are commonly present in low concentrations in food from non-contaminated areas, and these waste streams contain food-contact materials that have relatively high concentrations of PFAS [275]. Very little is known about the fate of PFAS in food waste during the anaerobic digestion process [347]. Composting food waste is becoming a common practice for recovering nutrients and producing soil amendments while avoiding methane and carbon-dioxide emissions resulting from the decomposition of food waste in landfills [345]. However, land application of compost can result in recycling PFAS back into the environment and food supply. Results from a recent study showed that 15 different PFAS compounds were detected in municipal food-waste compost, PFAS concentrations increased during composting, and food-contact materials (paper, plastic, coated metal) present in food waste were the greatest source of PFAS in food-waste compost [348]. Therefore, the separation of food-contact materials from food waste before composting can substantially reduce PFAS concentrations in compost. Results from another study showed that 68 different PFAS compounds were detected in food-contact materials, but toxicity hazard data are available for only 57% of the compounds found in food packaging [349]. Furthermore, results from another study showed that compostable food serviceware contained up to 13 different PFAS compounds, with some at relatively high concentrations, compared with the detection of only PFOS at a low concentration in fresh dairy manure, and no detectable PFAS in grass clippings and livestock bedding [350]. Comparatively, treated or composted biosolids have greater PFAS concentrations than food-waste compost, which contains greater concentrations than green waste or other organic composts [275]. These results indicate that composting food waste containing substantial amounts of food-contact materials and compostable food serviceware is a major source of PFAS when producing compost, which is a major concern for applications to soil to produce fruits and vegetables for human consumption, and field crops and forages for livestock production.

There are no standards for PFAS in compost or digestates from anaerobic digesters in the U.S., but some cities and states have implemented regulations to prohibit PFAS in food packaging, and some manufacturers are beginning to voluntarily phase out PFAS use in food-contact materials [275]. It is very difficult to test for PFAS in compost because EPA-approved laboratory procedures only apply to drinking water, each lab has its own modified method which makes comparing results across labs difficult, and testing is expensive if it is available. Furthermore, there are no methods for PFAS removal from compost other than to prevent using contaminated materials to produce them. Some states in the U.S. are implementing protective measures such as screening composts made from biosolids and requiring the collection and treatment of contact water from composting sites that accept food waste [275].

Proper management of animal manure is an essential component of a circular agri-food system to ensure that nutrients are recovered and recycled for productive purposes.

Beyond manure application as a soil amendment, anaerobic digestion to produce biogas has become an effective alternative recycling process, where residual digestate is then applied to cropland [351]. However, PFAS that may be present in manure from animals consuming PFAS-contaminated drinking water and feed are likely to become concentrated in the digestate. Furthermore, various methods are used to enhance biogas yield during anaerobic digestion, and little is known about the fate of various PFAS during these anaerobic digestion processes. Like composting, there is no technology available to remove PFAS from digestate from anaerobic digestion of manure other than preventing PFAS farther up the biological chain.

Unfortunately, there are limited options for altering agricultural practices to reduce PFAS contamination in plant- and animal-derived foods and waste streams (Table 10). In general, testing soil, water supplies, and animal-feed ingredients for the presence of PFAS contamination may minimize PFAS animal exposure on farms if point sources can be identified and not used. However, standardized analytical methodologies are needed to accurately quantify the large number of varying chemical composition of PFAS compounds in diverse biological matrices.

Table 10. Agricultural practices that reduce PFAS contamination in plant- and animal-derived foods and waste streams.

Practice
Test groundwater, surface water, and irrigation water supplies to determine the presence and concentrations of PFAS, and implement water treatment systems to remove PFAS in drinking water for livestock and poultry if needed
Avoid fruit, vegetable, pasture, and crop production from soil and water high-risk locations near airports, fire-training locations, industrial sites, and landfills
Avoid applying biosolids from human sewage treatment facilities on agricultural lands due to potentially high concentrations of PFAS
Properly apply non-PFAS animal manure to agricultural land to increase soil organic matter and decrease PFAS accumulation in plants
Avoid using hydroponics to grow vegetables in PFAS-contaminated areas which can increase plant accumulation in the absence of soil; avoid using hydroponics to grow vegetables in PFAS-contaminated areas which can increase plant accumulation in the absence of soil
Avoid feeding and using plant residues such as corn stover and wheat straw as bedding to livestock due to potentially high PFAS concentrations
Plant trees or construct wetlands in locations with PFAS-contaminated soil and water for bioremediation

11. How Do We Fix This Major One Health Problem?

Every person in every local community of every country around the world is entitled to have clean air to breathe, clean water to drink, and safe food to eat as a basic human right. As Brooks [352] eloquently summarized, "despite political pendulum swings, we must all keep our eyes on the horizon. The environmental and health threats facing our shared home persist, the opportunities to develop more sustainable solutions and practices remain timely, and realizing the Sustainable Development Goals for all people is necessary." Unfortunately, our ability to assess and monitor new environmental threats, such as PFAS, is limited because scientific analyses are incapable of keeping up with the amounts and types of chemicals released into the environment [353]. The widespread global contamination, environmental persistence, irreversible exposure, and toxic effects of even low concentrations of PFAS in soil, plants, food-producing animals, and humans are compelling indicators that PFAS have become a major One Health and sustainability problem.

Unfortunately, there is much less scientific and public awareness of the devastating effects of PFAS on the environment and all living things compared with other novel entities (i.e., microplastics), and the other eight planetary boundaries that cannot be exceeded if humanity is to exist and survive on Earth. Planetary boundaries are defined as scientific thresholds or limits in the Earth's atmosphere and ecosystems that must not be exceeded by human activities if we are to maintain a stable and resilient Earth ecosystem that will

ensure a safe operating space for human existence and survival [354,355]. Novel entities, which includes PFAS and microplastics, are one of the six (i.e., climate change, disrupted global nitrogen and phosphorus flows, functional and genetic biodiversity loss, freshwater use, land system change) of nine planetary boundaries that has been exceeded [353,356]. To make matters worse, studies have shown that microplastics act as carriers for PFAS, and their many complex interactions affect PFAS distribution, accumulation and toxic effects within ecosystems [357]. Although the persistence of these chemicals in the environment is often considered to be a less hazardous problem than toxicity, it is the main reason why these novel entity pollution problems have escalated into bigger problems because they spread over long distances, continually accumulate over time, and cause life-long exposure [356]. Although the combined toxicity of PFAS and microplastics is poorly understood, their coexistence and cumulative impact on the environment require the development of co-removal technologies to effectively mitigate them [357]. As a result, there is an urgent need to develop sustainable and bio-based alternative food packaging materials with similar physicochemical properties as found in current materials, but without the toxic effects.

Promising bio-based materials including plant polysaccharides, proteins, and waxes, along with recycled by-products and waste materials from agri-food industries that can be used to replace PFAS and plastics while also enhancing oxygen scavenging, moisture absorbing, and antimicrobial properties of sustainable food-packaging materials [358]. Until new safe and sustainable alternatives for PFAS and plastics are developed, our ability to control further environmental contamination is limited.

The extremely high environmental resilience and very slow degradation of PFAS results in only two fates, dilution or burial, if no mitigation actions are used [6]. There are a limited number of practices that consumers can adopt to limit PFAS exposure because of the pervasiveness of these "forever chemicals" (Table 4). There are no remediation practices that can be used to remove PFAS from the atmosphere, and limited methods to remove PFAS from water supplies (Table 5) and soil (Table 6). Although some remediation technologies for removing PFAS from contaminated water and soil are effective, most of them require many more years of development to make them technically and economically viable for practical implementation. Currently, the best methods for PFAS removal from contaminated water supplies involve filtration by reverse osmosis, or the use of membranes or activated carbon [20,217], and the most practical method for removing PFAS in soil appears to be ball milling [247,248]. However, these PFAS remediation techniques involve significant long-term resources and financial investment, have limited ability to remove short-chain PFAS compounds, and the effects that their use may have on local ecosystems are unknown [6]. There are also a lack of effective control measures and limited practices to reduce PFAS contamination in plant- and animal-derived foods and waste streams (Table 10). Phasing out one PFAS compound and replacing it with another of similar structure and function has been the most common industry practice [6]. However, this practice does not solve the problem of the continual production, use, and disposal of many types of PFAS in the environment. This global PFAS contamination and One Health problem can only be overcome by phasing out and banning future use of these forever chemicals.

There are numerous challenges in regulating PFAS [359]. First, because of the numerous applications, widespread use, and multiple benefits of PFAS in a long list of consumer products around the world, industries that produce or rely on these chemicals exert tremendous political pressure to prevent or limit regulations because of the economic losses that would be created in transitioning to safer alternatives. Furthermore, the lack of a universally accepted regulatory definition that adequately represents the diversity of the nearly 15,000 types of PFAS compounds, and the lack of uniform international standards and approaches for regulating PFAS among countries and regions has made it difficult

for businesses to track and ensure compliance across borders in complex global supply chains. In addition, the complex chemistry of PFAS and their multiple and diverse impacts on health and the environment require significant interdisciplinary research investment, which is expensive and time-consuming, to obtain comprehensive data on the hazards and risks of PFAS for informing effective regulations. Lastly, the current regulations of individual PFAS often result in industries substituting with other less studied PFAS compounds to avoid regulatory compliance, but this does not reduce their hazardous health and environmental effects.

Initial attempts to regulate the environmental contamination of PFAS began in 2009, when the Stockholm Convention of the United Nations Environment Programme listed two specific types of PFAS compounds, PFOA and PFOS, as persistent organic pollutants in Annex A, which involves eliminating production and use, and Annex C which aims to restrict the production and use of PFAS chemicals [9]. Since then, some voluntary and regulatory frameworks have been implemented for PFOS, PFOA, and a few other types of PFAS compounds including PFCAs, PFSAs, perfluorooctane sulfonamides (FOSAs), and perfluorooctane sulfonamidoethanols (FOSEs), at national or regional levels in the European Union and United States [360–362], but it is unclear if they have been effective in mitigating the harmful effects on humans, animals, plants, and the environment.

International and U.S. federal and state regulatory policies and guidance are complex and are influenced by numerous political, social, economic, and scientific factors [363]. Specifically, balancing the tradeoffs between the perceived benefits of PFAS on society versus the detrimental effects of PFAS on the environmental and human health has been the main determinant of the extent of development of PFAS regulations, but political will, social awareness, economic and scientific resource availability, and practical challenges have also contributed [364]. Unfortunately, because of various socioeconomic and political factors [228], regulations and standards to restrict or ban the use of PFAS to prevent further environmental contamination vary substantially among countries [359].

The EU and Canada have developed and implemented the most strict regulations aimed at reducing and controlling the production and use of PFAS. In Europe, the production and marketing of PFOA salts and precursors for all industrial uses including space exploration was banned in 2020 [364], and other PFAS compounds including PFOA, PFOS, PFNA, and PFHxS were restricted under a regulatory framework for food contaminants (https://www.oecd.org/en/topics/risk-management-risk-reduction-and-sustainable-chemistry.html, accessed on 17 January 2025). In 2023, the European Chemicals Agency proposed greater restrictions on the manufacture, marketing, and use of a broader group of PFAS rather than individual compounds [359]. The EU Reference Laboratory for halogenated POPs in feed and food developed a guidance document on analytical parameters to determine PFAS in food and feed [342], and the German Federal Institute for Risk Assessment [343] published guidelines recognizing that animal feed is key to compliance with maximum PFAS levels in food of animal origin. Some EU countries (i.e., Denmark, France, Germany, Sweden, The Netherlands) are enacting more strict PFAS regulations. For example, Denmark introduced a ban on the use of food contact materials containing PFAS, and The Netherlands has set stricter standards for monitoring and regulating PFAS contamination from industrial sources and maximum concentration limits of PFAS in groundwater and drinking water [359]. In Canada, the Canadian government implemented the final version of the Prohibition of Certain Toxic Substances Regulations in 2024 that further restricted the manufacture, use, sale, offer for sale, and import of three PFAS subgroups (PFOS, PFOA, and long-chain PFCAs) that were already regulated [359]. In addition, comprehensive risk assessments of PFAS by Environment and Climate Change Canada have led to prohibiting some types of PFAS in consumer products, environmental

monitoring, and promoting the development and use of safer alternatives [359]. Health Canada has also defined limits of different PFAS compounds in agricultural, industrial, and commercial soils [365].

In contrast, although the federal governments in the U.S. and Australia have provided some education, guidance, and standards regarding PFAS use and contamination, any regulatory action has been deferred to state and territory governments [363]. For example, although the U.S. Environmental Protection Agency has provided guidance for sampling methods to measure PFAS in potable and non-potable water, no published protocols are available for determining the presence and concentrations of PFAS in soil and forage crop samples, nor are there regulations or guidelines for hazardous limits in soils for agricultural or industrial industries [9]. Furthermore, there are no policies and government incentives for remediation of contaminated air, water, and soil [9]. However, several states in the U.S. (i.e., California, Colorado, Connecticut, Hawaii, Maine, Maryland, Minnesota, New York, Vermont, Washington) have implemented bans or restrictions on PFAS in various industrial and consumer products. For example, California law prohibits the manufacture, distribution. or sale of textiles and plant fiber-based food packaging that contain regulated PFAS, and requires companies to provide product labeling warnings for cookware and other consumer products containing PFAS [359]. Although the apparent disconnect between federal and state PFAS regulations in the U.S. may seem problematic, the current downsizing of regulatory agencies and deregulation at the federal level in the U.S. can be overcome by states maintaining and enacting more stringent PFAS regulations in the future.

Several countries in the Asia-Pacific region (i.e., Australia, China, Japan, New Zealand, Singapore, South Korea, Taiwan, Thailand, Vietnam) have integrated PFAS regulations into existing chemical regulation frameworks, and may require permits or licenses before manufacturing, importing, distributing, or using PFAS if they are not explicitly prohibited. Some Asia-Pacific countries are planning to implement more strict regulations comparable to those in the EU and U.S. for maximum PFAS limits in drinking water (Japan, Taiwan) and banning PFAS in cosmetics (New Zealand). In January 2025, Japan implemented regulations that prohibit the manufacture, import, and use of 138 PFAS compounds [359]. South Korea has imposed restrictions or bans on eight PFAS including PFOA, PFOS, PFHxS, PFBA, PFBS, PFHxA, and PFNA [359]. Unfortunately, other countries in Asia, Latin America (except Mexico and Brazil), and Africa have not developed or implemented PFAS regulations. China and Brazil continue to allow the production and use of PFOA and PFOS, even though they were designated to be eliminated from further use [363].

Unknown chemicals pose never-ending challenges for safety risk assessments [366], and there are several practical challenges in developing and implementing effective PFAS regulations [363]. The lack of an authoritative list of all PFAS compounds being used limits our ability to evaluate the health effects of all types of PFAS. It is infeasible to conduct complete toxicity assessments for each one of the nearly 15,000 PFAS compounds that have been produced and released into the global environment. Furthermore, some of the toxic effects of PFAS observed in animals may not be applicable to humans. Lastly, regulations are difficult to establish for a compound that provides numerous societal benefits unless there is clear and convincing scientific evidence that these compounds cause harm to humans and the environment. Regardless of these challenges, PFAS are a major One Health problem that urgently must be addressed through collaboration among governments, industry stakeholders, and the public to limit the production and use of these compounds and reduce their presence in our global ecosystem [357]. Because of the widespread global production, use, and environmental impact of PFAS, a coordinated global effort of cooperation, robust scientific research, and data sharing is needed to develop

harmonized regulatory frameworks and develop safer alternatives to PFAS to mitigate the detrimental effects on health and the environment.

12. Conclusions

There is no safe level of PFAS. The widespread global contamination, environmental persistence, irreversible exposure, and toxic effects of even low concentrations of PFAS in soil, plants, food-producing animals, and humans are compelling indicators that PFAS have become a major One Health and sustainability problem. Human exposure to PFAS causes detrimental health effects associated with nearly every organ (liver, kidneys, lungs, heart, brain, bones, and reproductive organs) and physiological system (circulatory, neural, endocrine, reproductive, and immune systems) in the human body. Novel entities, which includes PFAS and microplastics, are one of the nine planetary boundaries that has been exceeded, and the many complex interactions between these two categories of compounds affect PFAS distribution, accumulation, and toxic effects within ecosystems.

There are a limited number of practices that consumers can adopt to limit PFAS exposure because of the widespread presence of these "forever chemicals" in numerous consumer products. There are no remediation practices that can be used to remove PFAS from the atmosphere, limited methods to remove PFAS from water supplies and soil, and few practices that can minimize PFAS exposure of plants and animals. Therefore, PFAS production and use must be drastically curtailed except for critical uses. Research should be focused on developing bio-based materials including plant polysaccharides, proteins, and waxes, along with recycled by-products and waste materials from agri-food industries that can be used to replace PFAS and plastics while also enhancing the oxygen-scavenging, moisture-absorbing, and antimicrobial properties of sustainable food-packaging materials.

At the same time, industries must be required to pretreat water before discharging it into wastewater treatment plants to filter PFAS at the source and make the polluter responsible for cleaning up their own mess. Farmers must not spread sewage sludge on cropland and pastures, but should test soil for possible levels of PFAS contamination and should stop producing feed and food on contaminated soil. Consumers should ask marketers and manufacturers if their packaging and equipment are PFAS-free, and they should source food products only from farms that have not used biosolids as a soil amendment. Lastly, governments, industry stakeholders, and the public must collaborate to control the production and use of these compounds and reduce their presence and adverse health effects in our global ecosystem.

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Abbreviations

The following abbreviations are used in this manuscript:

EFSA	European Food Safety Authority
EU	European Union
FOSAs	Perfluorooctane sulfonamides
FOSEs	Perfluorooctane sulfonamidoethanols
PFAAs	Perfluoroalkyl acids

PFAS	Perfluoroalkyl and polyfluoroalkyl substances
PFBS	Perfluorobutanesulfonate
PFCAs	Perfluoroalkyl carboxylates
PFHxA	Perfluorohexanoate
PFHxS	Perfluorohexane sulfonate
PFNA	Perfluorononanoic acid
PFOA	Perfluorooctanoate
PFOS	Perfluorooctane sulfonate
PFSAs	Perfluoroalkane sulfonates
POPs	Persistent organic pollutants
U.S. EPA	United States Environmental Protection Agency

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