New
Contaminants

Perspective

Open Access

https://doi.org/10.48130/newcontam-0025-0005

Per- and polyfluoroalkyl substances in agriculture: environmental fate, bioaccumulation and management

Hui Li*

Received: 11 July 2025
Revised: 1 August 2025
Accepted: 18 August 2025
Published online: 5 September 2025

Abstract

Per- and polyfluoroalkyl substances (PFAS) represent a class of persistent synthetic chemicals that have been extensively utilized in industrial and consumer applications. Their environmental persistence, bioaccumulation, and toxicity have raised significant public concerns and led to regulation in some regions during the past two decades. This paper presents a brief review, focusing on the perspective of PFAS contamination in agriculture. Specifically, the paper elucidates the primary pathways by which PFAS enter agricultural systems. After PFAS chemicals enter the agricultural environment, soil serves as the sink and the sources accessible by biota such as crops, livestock, and wildlife. PFAS sorption by soil is characterized as a complicated dynamic process, with carbon-fluorine chain length as the major factor influencing their mobility and bioavailability. PFAS uptake and translocation in crops vary in plant species; short-chain PFAS demonstrate higher bioaccumulation in edible plant tissues, raising critical concerns regarding food safety. Livestock exposure to contaminated feed and water leads to PFAS bioaccumulation in animals and the derived food products, posing additional risks to human health. This perspective further briefs toxicological implications to human and ecosystem health, highlights current remediation and mitigation strategies, and assesses regulatory frameworks governing PFAS in the agricultural environment. Future research directions emphasize mechanistic understanding of plant and animal uptake, innovative remediation technologies, long-term environmental exposure and risk assessment, and regulation development. Immediate actions on PFAS contamination in agriculture are imperative to safeguard ecosystem integrity, food safety, and public health.

Keywords: PFAS, Biosolids, Agriculture, Sorption, Plant Uptake, Bioaccumulation, Regulation, Dietary exposure

Introduction

Per- and polyfluoroalkyl substances (PFAS) are a diverse group of synthetic organofluorine compounds that are characterized by multiple carbon-fluorine bonds and confer exceptional chemical stability and resistance to chemical and biological degradation in the environment. Nearly 15,000 PFAS chemicals have been identified, and many have been of industrial and commercial use in the applications of stain repellents, firefighting foams, food packaging, and textiles since the 1940s. Their widespread use and environmental persistence have resulted in global contamination, even in some remote regions. Due to their hydrophobic and lipophobic nature and high mobility, PFAS have been considered as 'forever contaminants' because they are recalcitrant to chemical and biological degradation, can accumulate in biota, and cause deleterious impacts to human and ecosystem health.

Drinking water contamination by PFAS has been the primary focus in public health; however, agricultural environments are now recognized as significant reservoirs and pathways for PFAS to enter food chains and transfer to humans. PFAS contamination in soils, crops, and livestock raises critical concerns for food safety, ecosystem health, and human exposure. This perspective attempts to provide a general overview of PFAS in agriculture, including pathways into agricultural systems, environmental fate in soils, plant and animal uptake, risks, management, regulatory considerations, and future research needs. The purpose is to attract more efforts to the research and management of PFAS contamination in agricultural production, which is essential to improving food safety and human health.

* Correspondence: Hui Li (lihui@msu.edu)
Full list of author information is available at the end of the article.

PFAS pathways into agricultural systems

PFAS enter agricultural systems via multiple environmental vectors, often related to anthropogenic activities and industrial sources. Land application of biosolids is one of the primary routes of PFAS introduction into agricultural soils. Biosolids are derived from the sewage sludge from wastewater treatment plants (WWTP). The wastewater treatment processes cannot effectively remove PFAS and cause their enrichment in sewage sludge. Biosolids contain a mixture of PFAS compounds, including many legacy contaminants such as perfluorooctane sulfonic acid (PFOS), and perfluorooctanoic acid (PFOA), as well as PFAS precursors. PFAS concentration in biosolids could vary widely, and some compounds can reach several micrograms per kilogram of dry weight[1,2]. The repeated land application of biosolids results in long-term PFAS accumulation in soils, with concentrations exceeding 1,000 ng/g in heavily biosolids-amended sites. Land application of biosolids is a common practice in the USA, European Union countries, and some Asian countries, which has represented a chronic source of soil contamination for decades.

The ineffective treatment of PFAS in wastewater results in their presence (e.g., short-chain PFAS) in the effluents from WWTP. In the regions experiencing water scarcity, the treated wastewater is often reused for irrigation, which could directly introduce PFAS into soils and crops. A study in South Korea detected the total PFAS concentration in irrigation water reaching 70 ng/L[3], which is sufficient to lead to progressive PFAS accumulation in soils and subsequent plant uptake over time. Current estimates suggest that 20% of agricultural lands in the USA have received land through biosolid application for plant nutrient supplementation, or irrigation with treated wastewater or contaminated surface and ground water, which is equivalent to 70 million acres of agricultural land that could have been contaminated with PFAS, although no reliable data source is provided.

Some PFAS can volatilize or be released as particulate-bound chemicals from industrial manufacturing facilities, firefighting activities, or landfill. Atmospheric transport facilitates their deposition onto agricultural land far from the source. For instance, near a fluorochemical manufacturing plant in North Carolina (USA), soil and crops within a 5-km radius showed significantly elevated PFAS concentrations, which could be attributed to transport in the atmosphere. This pathway is more apparent in regions near airports or military bases where aqueous firefighting foams (AFFFs) are frequently used in practical training and firefighting activities.

Local contamination hotspots are created when PFAS-containing AFFFs are applied during firefighting or training exercises. These foams contain high concentrations of PFAS (e.g., hundreds to thousands of milligrams of PFAS per liter), leading to soil and groundwater contamination around airports, military bases, and industrial sites. Direct spills or leaks of PFAS-containing chemicals also contribute to soil contamination[1]. Such hotspots pose significant risks to adjacent agricultural lands through surface-ground water interactions and contact with soil.

PFAS sorption and transport in soils

After their release into the soil, PFAS behaviors are governed by physicochemical processes and the specific structural characteristics of individual PFAS congeners. Long-chain PFAS, such as PFOS, exhibit strong sorption to soil organic matter via partitioning and adsorption on mineral surfaces, particularly iron and aluminum oxides, via electrostatic interactions[4]. The strong sorption leads to retention in top-soil horizons and less leaching potential to groundwater. For example, PFOS concentration drops exponentially by several orders of magnitude with soil depth[1]. In contrast, short-chain PFAS, such as perfluorobutanoic acid (PFBA), and perfluorobutane sulfonic acid (PFBS), are more water soluble and exhibit weaker sorption, resulting in elevated mobility and the potential for groundwater contamination[2,5,6]

Specific sorption, such as cation-bridging interaction or anion exchange, also contributes to the retention in soil, but the quantity remains unknown. Perfluoroalkyl carboxylic acids could strongly interact with multivalent cations such as Ca^{2+} and Fe^{3+} on the soil surface[7]. Soil solution pH, ionic strength, and composition also affect PFAS sorption to metal oxides in soils. PFAS sorption by iron and aluminum oxides in soil increases at a lower pH because of the increase in positive surface charges[8]. Research efforts to correlate PFAS sorption to individual soil properties fails to describe PFAS sorption by soil. A large knowledge gap exists in the elucidation of fundamental sorption mechanisms and the prediction of their transport in soils.

PFAS in surface soils could transport vertically to aquifers with the infiltrating water from precipitation, irrigation, runoff, and stormwater. The strongly sorbed PFAS generally demonstrate slower transport in soil. The amphiphilic features of PFAS can reduce their surface tension at the soil-air-water interfaces, and lead to enhanced accumulation. Sorption and enriched accumulation at soil-air-water interfaces both influence the retention and transport of PFAS particularly for long-chain PFAS compounds in soils[9]. Apparently, research progress has been made to better understand sorption and transport of PFAS in soil; however, the mechanism-based studies on sorption and transport under water-unsaturated conditions are still needed to advance the knowledge in these areas.

Plant uptake and bioaccumulation

Agricultural lands are the major reservoir for PFAS in the environment, and severely contaminated sites could exhibit PFAS concentrations at mg/kg levels[10,11]. A proportion of PFAS in soil can be released into the water and become bioavailable to plant uptake. Plants grown at contaminated sites are frequently detected with escalated PFAS concentrations[12]. Since PFAS compounds are typically associated with soil organic matter, clays, and metal oxides, their mobility and bioavailability to crop uptake may exhibit significant spatial and temporal variations in agricultural fields. Natural events (rain and wind), and farming practices (e.g., tillage, crop cultivation, and irrigation) can further complicate PFAS transport and plant uptake processes.

PFAS uptake by plants primarily occurs through absorption of PFAS with passive water mass flow to roots. Once inside the plant, PFAS translocate via the xylem to aerial tissues, including leaves, stems, fruits, and seeds. The bioaccumulation and distribution of PFAS in plants vary substantially in plant tissues. In general, PFAS bioaccumulation is greater in crop/vegetable stalks and leaves than in grains and fruits, indicating the preferential flow and bioaccumulation into vegetative tissues, rather than storage organs[13]. Short-chain PFAS chemicals commonly manifest greater translocation factors from plant roots to aboveground portions than long-chain homologues, which could be driven by transpiration streams in the xylem. In addition, the smaller short-chain PFAS molecular size could facilitate the transport through plant cell membranes. These factors could combine to cause the enhanced bioaccumulation of short-chain PFAS in plants. Different types of plants grown at the same location can demonstrate a wide variation in bioaccumulation for a given PFAS, which could be related to plant root morphology, protein/lipid content, and plant cell structures[14].

PFAS bioaccumulation in livestock

Consumption of PFAS-laden animal feeds and drinking contaminated water can lead to bioaccumulation in livestock living on farms[15].

Considering that crops and meat from livestock constitute major portions of human diets, consumption of PFAS-contaminated food represents a major exposure route responsible for the bioaccumulation of PFAS in humans. To guide the development of management solutions to mitigate PFAS bioaccumulation in livestock, it is imperative to clearly understand the fate, transport, and distribution of PFAS in agricultural farm settings, identify the sources, and characterize uptake processes for PFAS bioaccumulation in livestock.

Livestock can take up and accumulate PFAS from the ingestion of contaminated drinking water, consumption of polluted animal feeds, and dermal contact with contaminated soil. On the farms with PFAS-contaminated surface or ground water, even when no significant amount of PFAS was detected in soil or grass, the animals were still found to accumulate PFAS, which pinpoints the source as contaminated drinking water[16]. The consumption of PFAS-contaminated feed is another major exposure pathway for livestock, with particular concern about farms that received PFAS-contaminated biosolids. Livestock feed from these farms could contain a certain amount of PFAS which could transfer to livestock via feed consumption. PFAS compounds have been detected in liver, blood, muscle, milk, and urine of dairy cattle, primarily originating from contaminated silage consumption[17].

PFAS in livestock bodies are distributed in various tissues, primarily in serum, liver, and kidney, because of their strong affinity with certain proteins, e.g., albumin and hepatic proteins. PFAS can be eliminated from livestock and released into urine and feces. The clearance half-lives range from days to years depending on the specific chemical, animal sex, and age[18]. PFAS in animal bodies could be depurated to low and even to safe levels. In general, long-chain PFAS compounds demonstrate a relatively long half-life, and a slow clearance rate[18,19]. Urinary excretion is the primary clearance route for PFOA from sheep, while little PFOS was detected in urine; instead, approximately 5% of PFOS intake was excreted in the feces[20]. Short-chain PFAS, e.g., perfluorobutane sulfuric acid (PFBS), are distributed at trace levels in liver, kidney, plasma, and milk in dairy cattle, but present in a significant amount in the excretion of urine[21]. Although some data have been reported on PFAS bioaccumulation in livestock, few systematic studies have been conducted, which warrants further research on PFAS bioaccumulation and depuration in animals.

PFAS risks and management

The persistence of PFAS in agricultural products poses risks to consumers. Chronic exposure to a low doses of PFAS via food consumption is an emerging concern, especially for populations relying on locally grown produce and animal products in PFAS-contaminated regions. Vulnerable groups, such as children and pregnant women, face elevated health risks due to bioaccumulation, toxicity, and long elimination periods. PFAS in the human body have been identified to be associated with immunotoxicity, endocrine disruption, hepatotoxicity, reproductive and developmental effects, and carcinogenicity[22]. The corresponding mechanisms could involve the interference with nuclear receptors, hormonal pathways, and cellular signaling.

To minimize PFAS exposure via food consumption, the European Union has established a Commission Regulation 2023/915 on maximum levels (around ng/g) in certain foods (e.g., fish, eggs, beef, pork, and poultry) for specific PFAS and the sum of PFOS, PFOA, perfluorononanoic acid (PFNA), and perfluorohexane sulfonic acid (PFHxS). Although the European Union has made progress in regulating PFAS in food and potentially in food-contacting materials in the near future, regulatory guidelines for PFAS in agricultural matrices are still limited in scope in other countries. The US regulation focused more on PFAS in drinking water. In May 2025, the USEPA set enforceable maximum contaminant levels at four nanograms per liter of water (ppt), but there is a lack of regulation of PFAS in soil or food matrices. Several states in the USA, such as California, Maine, and Michigan, have set up PFAS limits for land-applied biosolids or banned this practice, and proposed maximum allowable PFAS concentrations in various food products, though enforceable levels remain under development. The lack of sound data and uniform guidelines complicates accurate risk assessment of PFAS and their environmental management. Effective management demands integrated PFAS monitoring in environmental matrices, surveillance of food safety, and appropriate agricultural best practices to mitigate PFAS entry into food products with a sound policy setup. It is essential to involve multi-stakeholders by the collaboration of regulatory agencies, farmers, industrial manufactures, environmental engineers, and scientists to address this critical issue.

Future research directions and perspectives

Food produced from PFAS-impacted agricultural lands could cause PFAS accumulation in crops at low ng/g levels, which could pose concerns and potential risks to human health because of the chronic dietary exposure. PFAS could also enter livestock, and lead to trace-level residues in animal-derived foods. Since PFAS can be accumulated in humans and have long-term biological half-lives, consumption of contaminated produce contributes a substantial portion of PFAS to the total burden in the human body. Monitoring PFAS in foodstuffs and mitigating PFAS accumulation in food production are therefore critical to human health and warrant tackling the issues from the perspective of multi-stakeholders including farmers, industrial manufactures, residents, scientists, and policy makers. Solving PFAS contamination in agriculture needs integrative multidisciplinary research and outreach priorities:

• Mechanistic studies: Detailed molecular and physiological investigations on PFAS uptake, translocation, and metabolism in various crop species and animals are needed to identify the key features and processes conferring low uptake and bioaccumulation, and high depuration rate. The results could inform breeding or genetic engineering approaches in plants and animals to interfere with PFAS uptake and bioaccumulation.

• Long-term field-scale research: Multiyear, large-scale field studies should be conducted to assess PFAS fate and bioaccumulation in the farms with varying soil types, climates, and agronomic practices, to generate robust data to develop exposure and risk models.

• Ecotoxicology: The comprehensive assessment of ecosystem-level consequences is essential to evaluate the impacts of PFAS on soil microbiomes, beneficial insects, and non-target organisms.

• Pharmacokinetics in livestock: More systematic studies on PFAS distribution in animal tissues, excretion pathways, and transfer into edible products will improve the accuracy in the assessment of human exposure to PFAS via food consumption.

• Remediation technologies: Development of cost-effective soil remediation technologies by combining sorption, sequestration, decomposition, and soil amendment strategies is imperative, and technologies need to be validated at the field scale to assess their performance and feasibility before extending to remediate PFAS contamination on farms.

• Food safety: Expansion of routine PFAS analysis in agricultural products, coupled with epidemiological studies on dietary exposure, is essential to protecting vulnerable populations. PFAS accumulation in crops and livestock at low ng/g levels could cause detrimental impacts to human health because of the chronic dietary exposure to PFAS-containing food.

• Regulatory frameworks: Science-based regulations must be developed globally to control PFAS in soil, water, and food matrices to effectively mitigate PFAS risks to human and ecosystem health.

Author contributions

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, manuscript preparation, and approval of the final version of the manuscript.

Data availability

All data used in this article are derived from public domain resources.

Fundings

This work was supported in part by USEPA STAR Program (No. 84095601), USDA National Institute of Food and Agriculture (2022-67019-36487), and Michigan AgBioResearch (MICL02614). This document has not been formally reviewed by the funding agencies. The views expressed in this document are solely from the author and do not necessarily reflect those of the funding agencies. The agencies do not endorse any products or commercial services mentioned in this paper.

Declarations

Competing interests

The authors declare that they have no conflict of interest.

Author details

Department of Plant, Soil, and Microbial Sciences, and Center for PFAS Research, Michigan State University, East Lansing, Michigan 48824, USA

References

[1] Brusseau ML, Anderson RH, Guo B. 2020. PFAS concentrations in soils: background levels versus contaminated sites. *Science of the Total Environment* 740:140017
[2] Sepulvado JG, Blaine AC, Hundal LS, Higgins CP. 2011. Occurrence and fate of perfluorochemicals in soil following the land application of municipal biosolids. *Environmental Science & Technology* 45(19):8106−8112
[3] Yoo H, Washington JW, Jenkins TM, Ellington JJ. 2011. Quantitative determination of perfluorochemicals and fluorotelomer alcohols in plants from biosolid-amended fields using LC/MS/MS and GC/MS. *Environmental Science & Technology* 45(19):7985−7990
[4] Li F, Fang X, Zhou Z, Liao X, Zou J, et al. 2019. Adsorption of perfluorinated acids onto soils: kinetics, isotherms, and influences of soil properties. *Science of The Total Environment* 649: 504-514
[5] Navarro I, de la Torre A, Sanz P, Porcel MÁ, Carbonell G, et al. 2018. Transfer of perfluorooctanesulfonate (PFOS), decabrominated diphenyl ether (BDE-209) and dechlorane plus (DP) from biosolid-amended soils to leachate and runoff water. *Environmental Chemistry* 15(4):195−204
[6] Xiao F, Simcik MF, Halbach TR, Gulliver JS. 2015. Perfluorooctane sulfonate (PFOS) and perfluorooctanoate (PFOA) in soils and groundwater of a US metropolitan area: migration and implications for human exposure. *Water Research* 72:64−74
[7] Wang W, Rhodes G, Zhang W, Yu X, Teppen BJ, et al. 2022. Implication of cation-bridging interaction contribution to sorption of perfluoroalkyl carboxylic acids by soils. *Chemosphere* 290:133224
[8] Oliver DP, Li Y, Orr R, Nelson P, Barnes M, et al. 2019. The role of surface charge and pH changes in tropical soils on sorption behavior of per-and polyfluoroalkyl substances (PFASs). *Science of The Total Environment* 673:197−206
[9] Lyu Y, Wang BH, Du XQ, Guo B, Brusseau ML. 2022. Air-water interfacial adsorption of C4-C10 perfluorocarboxylic acids during transport in unsaturated porous media. *Science of the Total Environment* 831:154905
[10] Jin H, Zhang Y, Zhu L, Martin JW. 2015. Isomer profiles of perfluoroalkyl substances in water and soil surrounding a Chinese fluorochemical manufacturing park. *Environmental Science & Technology* 49(8):4946−4954
[11] Felizeter S, Jürling H, Kotthoff M, De Voogt P, McLachlan MS. 2020. Uptake of perfluorinated alkyl acids by crops: results from a field study. *Environmental Science: Processes & Impacts* 23(8):1158−1170
[12] Wang W, Rhodes G, Ge J, Yu X, Li H. 2021. Uptake and accumulation of per- and polyfluoroalkyl substances in plants. *Chemosphere* 261:127584
[13] Krippner J, Falk S, Brunn H, Georgii S, Schubert S, et al. 2015. Accumulation potentials of perfluoroalkyl carboxylic acids (PFCAs) and perfluoroalkyl sulfonic acids (PFSAs) in maize (*Zea mays*). *Journal of Agricultural and Food Chemistry* 63(14):3646−3653
[14] Xiang L, Chen L, Yu LY, Yu PF, Zhao HM, et al. 2018. Genotypic variation and mechanism in uptake and translocation of perfluorooctanoic acid (PFOA) in lettuce (*Lactuca sativa* L.) cultivars grown in PFOA-polluted soils. *Science of the Total Environment* 636:999−1008
[15] Lupton SJ, Smith DJ, Scholljegerdes E, Ivey S, Young W, et al. 2022. Plasma and skin per- and polyfluoroalkyl substance (PFAS) levels in dairy cattle with lifetime exposures to PFAS-contaminated drinking water and feed. *Journal of Agricultural and Food Chemistry* 70:15945−15954
[16] Mikkonen AT, Martin J, Upton RN, Barker AO, Brumley CM, et al. 2023. Spatio-temporal trends in livestock exposure to per- and polyfluoroalkyl substances (PFAS) inform risk assessment and management measures. *Environmental Research* 225:115518
[17] Vestergren R, Orata F, Berger U, Cousins IT. 2013. Bioaccumulation of perfluoroalkyl acids in dairy cows in a naturally contaminated environment. *Environmental Science and Pollution Research* 20(11):7959−7969
[18] Death C, Bell C, Champness D, Milne C, Reichman S, et al. 2021. Per-and polyfluoroalkyl substances (PFAS) in livestock and game species: a review. *Science of the Total Environment* 774:144795
[19] Lupton SJ, Dearfield KL, Johnston JJ, Wagner S, Huwe JK. 2015. Perfluorooctane sulfonate plasma half-life determination and long-term tissue distribution in beef cattle. *Journal of Agricultural and Food Chemistry* 63(51):10988−10994
[20] Kowalczyk J, Ehlers S, Fürst P, Schafft H, Lahrssen-Wiederholt M. 2012. Transfer of perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) from contaminated feed into milk and meat of sheep: pilot study. *Archives of Environmental Contamination and Toxicology* 63(2):288−298
[21] Kowalczyk J, Ehlers S, Oberhausen A, Tischer M, Fürst P, et al. 2013. Absorption, distribution, and milk secretion of the perfluoroalkyl acids PFBS, PFHxS, PFOS, and PFOA by dairy cows fed naturally contaminated feed. *Journal of Agricultural and Food Chemistry* 61(12):2903−2912
[22] Sunderland EM, Hu XC, Dassuncao C, Tokranov AK, Wagner CC, et al. 2019. A review of the pathways of human exposure to poly- and perfluoroalkyl substances (PFASs) and present understanding of health effects. *Journal of Exposure Science and Environmental Epidemiology* 29(2):131−147