Occurrence of PFAS in the specialty crop production: State of the Science review

Key takeaways:

- A family of compounds known as PFAS are recognized by regulatory agencies worldwide as a contaminant.
- PFAS are ubiquitous in households (non-stick cookware, some microwave-safe single-use containers, certain wrinkle-free and stain-free textiles and surface treatments) and in the environment (jet fuel, grease-resistant coatings, firefighting foam).
- Repeated FDA supermarket surveys of fresh produce detected either no or only traces of PFAS in fresh produce. Commonly found in shellfish, seafood, some ultra-processed foods.
- Soils and ag water in production areas located away from PFAS manufacturing facilities, airports, large urban areas are generally free from PFAS.
- Common sources of PFAS contamination (biosolids, urban run-off) are already excluded from specialty crop production for FSMA compliance.

Executive summary

Per- and polyfluoroalkyl substances (PFAS) are a large and diverse class of over 12,000 synthetic compounds, recognized as environmental contaminants of concern due to their persistence and potential health risks (National Academy of Sciences, 2022). PFAS can enter the environment through three main pathways--emissions from manufacturing facilities, landfill leachate, and discharges from wastewater treatment plants. Human exposure primarily occurs via ingestion, inhalation, and dermal contact, with ingestion of contaminated food and water being the most common route. Inhalation of dust or airborne PFAS and dermal contact with certain products also contribute to overall exposure. Global regulatory framework aiming to exclude PFAS from foods, waters and the environment is rapidly evolving.

PFAS are ubiquitous and used in thousands of consumer and industrial products, including nonstick cookware, firefighting foams, jet fuel, and protective gear. A review of 52 studies that examined 15 categories of consumer products—encompassing 1,040 individual items—identified 107 distinct PFAS (Dewapriya et al., 2023). PFAS concentrations in consumer products varied widely, ranging from 0.26 parts per trillion (ppt) to 29,000 parts per million (ppm). The highest average concentrations were detected in textiles, followed by household chemicals, then cosmetics. Firefighting products exhibited the highest mean PFAS concentration, with 39 products showing an average of 488.51 ppm (range: 0.11–11,031.30 ppm) (Benotti et al., 2020;

Favreau et al., 2017a, 2017b; Fiedler et al., 2010; Herzke et al., 2012; Weiner et al., 2013). Textile finishing agents reported a mean concentration of 302.92 ppm (range: 2.92–1,370.00 ppm) across 12 products (Mumtaz et al., 2019). Ten studies evaluating household chemicals—covering 122 products—had an aggregated mean PFAS concentration of 208.08 ppm (range: 0.0005–3,490.60 ppm) (Blom and Hanssen, 2015; Borg, 2017; Favreau et al., 2017a, 2017b; Fiedler et al., 2010; Guo et al., 2009; Herzke et al., 2012; Kotthoff et al., 2015; Liu et al., 2014; Liu et al., 2015).

FDA repeated sampling of fruit and vegetable samples from retail outlets detected either no PFAS at all or only low traces of PFAS over the 4-year sampling period (2019-2023). Foods of animal origin, on the other hand, were an important contributor to human exposure to PFAS based on the same survey. Fish and shellfish can accumulate PFAS from polluted waters, making them a notable dietary source. Similarly, animals that graze on contaminated land or drink tainted water may accumulate PFAS in their meat and in dairy products. Drinking water can also become contaminated through leaching from landfills, industrial sites, and other polluted areas.

While biosolids (treated sewage sludge) are often contaminated with PFAS and can contaminate soils, the use of biosolids in horticulture is already limited because of grower's intent to comply with FSMA. In the soils that did not experience recent biosolid deposition or a run-off from highly contaminated sites, levels of PFAS are very low (although academic studies detected very low levels of PFAS in remote areas). Under laboratory conditions, there is evidence of PFAS uptake by plants.

Global and national PFAS regulatory frameworks

The global regulatory landscape for PFAS is evolving rapidly, with increasingly stringent measures in response to the growing awareness of their environmental persistence and potential human health risks. Globally, the Stockholm Convention on Persistent Organic Pollutants—a multilateral environmental treaty (which is not ratified by the United States and 4 other countries)—has banned or restricted the use of several PFAS, including PFOS, PFOA, and PFHxS (Stockholm Convention, 2025).

The U.S. Food and Drug Administration (FDA) has not established legal limits for PFAS in food. However, the agency monitors its presence through its ongoing Total Diet Study (TDS). As part of this study, the FDA has tested a wide range of foods—including meat, seafood, dairy products, produce, and processed items, such as baby food and canned goods—for PFAS. Since 2019, the FDA has tested nearly 1,300 additional food samples from the U.S. market, including over 400 from areas with known PFAS contamination (not intended for sale). Over 97% of the samples had no detectable PFAS. However, some seafood (fish sticks, tuna, and cod) and one ground beef sample showed detectable PFAS (Food and Drug Administration, 2022), with follow-up studies in 2023 revealing PFAS in 14 of 32 (44%) seafood samples, and in 60 of 81 (74%) of samples in its

2022 targeted seafood survey. One small study in Fayetteville, NC—a PFAS-contaminated area—reported PFAS in 16 of 20 produce samples. While this raises potential health concerns, the FDA warned that the small sample size limits generalizability of the results. The FDA continues to evaluate PFAS levels in food through its ongoing TDS and targeted surveys, focusing particularly on seafood, to decide whether more or broader sampling is needed. While the FDA has stated that current PFAS levels in the food supply are not a major health concern, the agency continues to investigate and evaluate its potential impact. While 11 states have enacted laws related to PFAS in food packaging, Maine is the only state to establish a current PFOS Action Level for food -- beef at 3.4 parts per billion (ppb) in addition to its milk PFOS Action Level of 210 ppt, which is part of the PFAS in Products Program (An Act to Stop Perfluoroalkyl and Polyfluoroalkyl Substances Pollution, 2021). In January 2025, the FDA issued a Federal Register Notice declaring that 35 food-contact notifications for PFAS-based grease-proofing agents used in paper and paperboard packaging are no longer effective, following discontinuation of their use. In addition to federal action, eleven U.S. states—California, Colorado, Connecticut, Hawaii, Maine, Maryland, Minnesota, New York, Rhode Island, Vermont, and Washington—have enacted laws or regulations to restrict or ban the use of PFAS in food packaging.

A lawsuit, *Tucson Environmental Justice Task Force, et al. v. FDA*, Case No. 4:25-cv-00035-JAS, was filed on January 24, 2025, in the U.S. District Court for the District of Arizona. The filing followed a legal petition submitted in November 2023 by the Tucson Environmental Justice Task Force, which urged the FDA to establish limits on certain PFAS chemicals the agency has detected in foods such as blueberries, lettuce, milk, and salmon. Pursuant to a motion for a continuance and a subsequent court order granting it, the FDA has committed to responding to the Citizen Petition by the end of 2025. The court further ordered that the case be continued, with the parties required to file a joint status report within 14 days of the FDA's response to the Citizen Petition or by December 31, 2025—whichever occurs first.

The U.S. Environmental Protection Agency (EPA) established legally enforceable maximum contaminant levels (MCLs) for PFAS in drinking water under the National Primary Drinking Water Regulation (0.4 parts per trillion (ppt) for PFOA (perfluorooctanoic acid) and PFOS (perfluorooctane sulfonic acid) and 10 ppt for PFNA (perfluorononanoic acid), PFHxS (perfluorohexane sulfonic acid), and HFPO-DA (GenX chemicals) (EPA, 2025). Within their regulatory sphere, the EPA has concluded that there is no safe level of exposure to PFOA or PFOS. Beyond water quality standards, the EPA also regulates PFAS through restrictions on their manufacture and by designating certain PFAS as hazardous substances. In response to rising concerns over PFAS exposure, the U.S. Agency for Toxic Substances and Disease Registry (ATSDR), a federal agency embedded with the U.S. Department of Health and Human Services, proposed updated Minimal Risk Levels (MRLs) for oral ingestion of four major PFAS compounds. Developed under the statutory authority of CERCLA Section 104(i), 42 U.S.C. § 9604(i), these MRLs are designed as health-based screening values—not regulatory cleanup standards. The newly proposed reference doses are: 3×10^{-6} mg/kg/day for PFOA; 2×10^{-6} mg/kg/day for PFOS; 2×10^{-5} mg/kg/day for PFHxS, and 3×10^{-6} mg/kg/day for PFNA. The ATSDR reference doses for PFOA and PFOS are, respectively, 7-10X more stringent than the reference doses used to calculate the 2016 EPA health advisories, setting a combined limit of 70 ppt for these chemicals in food and water, but did not set any reference dose for PFHxS and PFNA (National Academy of Sciences, 2022).

In 2018, the European Food Safety Authority (EFSA) identified fish, meat, eggs, and products containing these ingredients as major contributors to adult dietary exposure to perfluorooctane sulfonic acid (PFOS), a common PFAS (EFSA, 2018). To address this issue, the European Union (EU) has proposed restrictions under the REACH (Registration, Evaluation, Authorization, and Restriction of Chemicals) regulation—potentially the most comprehensive PFAS ban in EU history (European Commission, 2025). The EU also established a group tolerable weekly intake (TWI) of 4.4 ng/kg body weight for the combined exposure to four widely used PFAS: PFOS, PFOA, PFNA, and PFHxS. Furthermore, under EC Recommendation 2022/1431, the European Commission advises Member States to monitor PFAS levels in food between 2022 and 2025, including a variety of foods (fruits, vegetables, starchy roots, seaweed, cereals, nuts, oilseeds, infant foods, animal-based products, non-alcoholic beverages, wine, and beer) (European Commission, 2022). Australia is also taking action by restricting the import, manufacture, export, and use of these substances. Similar to the European Commission, Japan has implemented regulations on PFAS, including the establishment of daily intake limits for certain PFAS in food and beverages.

While the EFSA (2018) has issued some of the most stringent guidance regarding PFAS in food, it has not directly banned PFAS in food-contact materials. Nevertheless, EFSA has published scientific opinions and guidance on the health risks associated with PFAS in food, including those originating from packaging, and has recommended actions to reduce exposure. Denmark took early regulatory action, enacting a ban in 2019 on the use of PFAS in paper- and cellulose-based food packaging, which took effect in 2020 (Denmark Ministry of Food, Agriculture, and Fisheries, 2020). Furthermore, in January 2023, five EU member states submitted a proposal to the European Chemicals Agency (ECHA) to restrict all non-essential uses of PFAS—including in food packaging. The proposal aims to ban the use and importation of approximately 10,000 PFAS compounds (European Chemicals Agency, 2023).

Potential sources and fate of PFAS in specialty crop production environments

Sources and fate of PFAS in soils. PFAS poses a significant threat to agricultural systems, entering agricultural lands through application of biosolids, use of contaminated irrigation water, and proximity of agricultural lands to point sources (e.g., airports and military installations). Once introduced, PFAS can degrade soil and water quality, disrupt crop production, and pose risk to livestock health. Brusseau et al. (2020) compiled meta-data from over 30,000 samples representing >2,500 global sites across all continents. For soil survey studies (5700 soil samples collected from >1,400 sampling locations across the world), the median PFOA and PFOS concentration was 2.7 µg/kg (range: 0.01 µg/kg to 123.6 µg/kg) and 2.7 µg/kg (range: 0.003 µg/kg to 162 µg/kg), respectively. For PFOA and PFOS concentrations in soil meta-data for primary-source contaminated sites the median was much higher 83 µg/kg (range: 2-11,484 µg/kg) and 8,722 µg/kg (range: 0.4-460,00 µg/kg), respectively. Median PFOA and PFOS concentrations for secondary-source contaminated sites was 38 µg/kg (range: 0.8-2,531 µg/kg) 680.5 µg/kg (range: 0.4-5,500 µg/kg), respectively. PFAS concentrations at primary-source contaminated sites (such as areas near PFAS manufacturing facilities, airports, etc.) were much higher than background levels, particularly for PFOS, with maximum concentrations reaching several hundred mg/kg. Depth profile analyses also revealed PFAS retention in the vadose zone over decades and evidence of leaching into groundwater. These findings underscore the role of soil as a major long-term reservoir for PFAS. In areas near fluorochemical manufacturing or processing facilities, PFAS was detected in both surface and groundwater. While concentrations in regions without primary-source contaminated sources generally were below detection limits or occurred at ppt levels, those near point sources commonly exhibited concentrations in the ppb range or higher (Janda et al., 2019; Pan et al., 2011). Importantly, Brusseau's meta-analysis confirmed PFAS is ubiquitous, detected in remote regions, far from known contamination sources.

While the EPA does not have specific, nationally enforceable soil standards for PFAS, it does provide Regional Screening Levels (RSLs). RSLs are not enforceable limits, they are advisory guidelines used for assessing risk and guiding site investigations. The RSLs are used by EPA and state agencies to assess and characterize potential remediation sites, rather than as strict, regulatory limits. Many states have established their own soil standards for PFAS, which may vary in terms of the specific compounds covered and the levels set. Five have established threshold values for PFAS in soil (Alaska, Connecticut, Massachusetts, New Jersey, Texas). Additionally, some U.S. states may have standards for protecting groundwater from PFAS contamination, which would translate to low threshold values for soil impacts. The EPA's RSLs provide guidance for different types of soil (residential vs. industrial) and for various PFAS compounds

Table 1. Most common Regional Screening Levels (RSLs).

PFAS Compound	**Residential Soil Level (mg/kg)**	**Industrial Soil Level (mg/kg)**
PFOS	0.13	1.6
PFOA	0.19	2.5
PFNA	0.19	2.5
HFPA-DA ("GenX")	0.23	3.5

PFHxS	1.3	160
PFBS	19	2500
PFHxA	32	410
PFBA	78	1200

Prevalence in soil amendments. Under the Food Safety Modernization Act (FSMA), the use of biosolids—treated sewage sludge derived from human waste—is strictly regulated in the cultivation of fresh fruits and vegetables. Although biosolids are not classified as Biological Soil Amendments of Animal Origin (BSAAO) under the Produce Safety Rule (PSR), their application is nonetheless restricted. According to 21 CFR §112.53, human waste may only be used if it has been treated in accordance with the Environmental Protection Agency’s biosolids rule (40 CFR Part 503) and applied in a manner that prevents contact with covered produce during or after application, as well as avoiding contamination throughout the growing and harvesting process. Even when biosolids meet EPA standards for pathogen and vector reduction and comply with heavy metal limits, their use remains limited in the United States. FSMA does not endorse or recommend the use of biosolids, placing the burden of proof on the grower to demonstrate that their application poses no risk of contamination. Consequently, most produce growers avoid biosolids, opting instead for more widely accepted alternatives such as composted animal manure or treated poultry litter. When managed according to FSMA microbial standards and required pre-harvest intervals, these alternatives are more compatible with Good Agricultural Practices (GAPs) and third-party food safety certification programs. Additionally, the use of sewage sludge is explicitly prohibited in organic farming under Title 7, Subpart C (Organic Production and Handling Requirements), §205.203. Outside the United States, however, biosolids are more widely used as soil amendments and fertilizers, with the Asia-Pacific region accounting for 35% of the global biosolids market. Nonetheless, global adoption is often limited by concerns over heavy metal contamination (Ajibola & Zwiener, 2022; Siebielec et al., 2018; Urbaniak et al., 2017).

Under 40 CFR Part 503, biosolids are classified as Class A (pathogen-free, unrestricted use) or Class B (some pathogens, restricted use with required site management), with additional state permitting in some cases. Currently there is no federal regulation specifically addressing PFAS in biosolids, so individual U.S. states determine their own management practices. In 2022, a nationwide survey from the Environmental Council of the States (ECOS) collected data about PFAS-related policies, testing, and communication challenges. Thirty-four (34) states responded to the survey. Maine is the only state that prohibits land application of biosolids. Thirteen states allow the use of land-applied biosolids, with allowances based on the class of biosolids. Federally, the EPA regulates biosolids under the Clean Water Act (CWA) Section 405(d) through 40 CFR Part 503, which sets standards for pollutant limits, pathogen and vector attraction reduction, and management practices to protect human health and the environment.

In a recent study, one of the few conducted on operational farms, researchers examined PFAS contamination on 10 farms treated with biosolids using a paired control-treatment design (Oviedo-Vargas et al., 2025). PFAS concentrations were significantly higher in biosolids-treated soils compared to untreated control soils. Soil depth, soil physicochemical properties (e.g., organic matter and pH), and biosolids source influenced the concentrations and types of PFAS found in treated soils. Most PFAS concentrations in surface (0–15 cm) treatment soils were positively correlated with Zn, Cu, and S. These correlations could be due to biosolids with a relatively higher content of PFAS potentially having also relatively higher content of Zn, Cu, and S. SOM, soil organic carbon (SOC), and soil total carbon (TC) were also positively correlated with PFHpA, PFNA, PFDA, PFUnA, PFTrDA and PFAS concentrations. However, no significant differences between control and treatment fields were observed for SOM, SOC, or TC, suggesting correlations between PFAS and SOM content is driven by PFAS interactions with SOM, as opposed to an inherited increase in SOM resulting from biosolids use. All individual PFAS concentrations in the treatment soils were negatively correlated with pH, which ranged from 6.1 to 7.5. Lower pH may favor the partition of PFAS onto soil versus water then increase PFAS soil concentrations. Overall, SOM content and pH appear to play a role in the presence of PFAS in treatment soils, with implications for their mobility through the soil profile. Other soil properties, such as texture and its effects on air–water interfacial area could also be important drivers of soil PFAS dynamics. With the exception of three treatment fields, vertical migration of PFAS was evident, as concentrations were detected in both surface and subsurface layers. In most cases, PFAS concentrations in the subsurface layer were lower than those in the surface layer, supporting the occurrence of vertical PFAS migration. These results agree with other studies evaluating biosolids-derived PFAS at multiple soil depths (Alvarez-Ruiz et al., 2024; Pepper et al., 2021; Sepulvado et al., 2011; Washington et al., 2010).

In a well-documented case in Alabama (Washington et al., 2010), the use of biosolids from wastewater treatment plants—receiving waste from industries that manufacture or use PFAS—was linked to significant soil, groundwater, and food contamination. Biosolids generated at a wastewater treatment plant in Decatur, Alabama, had been applied to agricultural fields for more than a decade. Waste-stream sources during this period included industries that work with fluorotelomer compounds and sludges from this facility were found to be elevated in perfluoroalkylates (PFAs). Samples from the biosolids-applied fields had PFAS at much higher concentrations than in the background fields; generally the highest concentrations were perfluorodecanoic acid (≤990 ng/g), perfluorododecanoic acid (≤530 ng/g), perfluorooctanoic acid (≤320 ng/g), and perfluorooctane sulfonate (≤410 ng/g). Contrasts in PFA concentration between surface and deeper soil samples were more pronounced in long-chain congeners than shorter chains, suggesting relatively lower environmental mobilities for longer chains.

Pepper et al. (2021) conducted a field study in Pima and Pinal County, AZ, involving multiple agricultural plots that received land application of Class B biosolids from 1984 to 2019 also investigated the impact of long-term land application of biosolids on PFAS presence in soils. Relatively low mean concentrations of PFAS ranging from non-detect to 1.9 µg/kg were measured in soil samples collected from sites used for agriculture and that received irrigation with groundwater but never received biosolids. PFAS concentrations in soils amended with biosolids were similarly low, ranging from non-detect to a mean concentration of 4.1 µg/kg. PFAS detected in samples of irrigation water were also present in the soil. These levels of detection are well below EPA recommendations for residential soils (see Table 1).

While biosolids are documented as a source of PFAS in production areas, it should be noted that their use in specialty crop production in the US is highly unlikely due to a number of regulations that limit their application in horticulture.

Sorption and mobility. An accurate prediction of PFAS sorption in soil is critical for conducting an environmental risk assessment. PFAS molecules sorbed to soil particles become unavailable for plant uptake. Sorption of PFAS in soil is influenced by several factors—pH, presence of cations, carbon chain length, and soil organic matter (SOM) (Pereira et al., 2018). pH and cation effects are complex and compound dependent. Sorption generally increases as pH decreases (Chen et al., 2009; Higgins and Luthy, 2006; Pereira et al., 2018; Zhang et al., 2013). The addition of specific cations, particularly for intermediate-chain PFAS compounds, enhances sorption, especially at higher pH levels. However, these effects were less pronounced for long-chain PFAS, which pH alone was a more critical factor than cation presence, as added cations had limited effect. Magnesium (Mg^{2+}), iron (Fe^{3+}), and aluminum (Al^{3+}) have also been shown to positively affect PFAS sorption (Wang et al., 2015). Chain length also plays a key role in PFAS behavior in soils. Longer-chain PFAS generally sorb more strongly to soil particles, reducing their mobility but increasing their persistence in the soil matrix (Ahrens et al., 2010; Higgins and Luthy, 2006; Pereira et al., 2018). In contrast, shorter-chain PFAS are more soluble in water and more mobile, making them more likely to leach into groundwater and penetrate deeper soil layers. Additionally, sorption of shorter-chain PFAS was more strongly affected by soil organic matter (SOM) bulk net charge, which increased with increased pH. The type of cation also influenced SOM charge. The largest increase in SOM net charge was observed with Na^+ (10 mM), followed by Ca^{2+} (3 mM and 5 mM), while Al^{3+} (2 mM) demonstrated the lowest net charge at $pH < 5$. Sorption is influenced by factors, such as pH, cations, PFAS chain length, and soil organic matter (SOM). Sorption generally increases with decreasing pH, and specific cations can enhance sorption—especially for intermediate-chain PFAS—though long-chain PFAS are more affected by pH alone. Longer-chain PFAS tend to bind more strongly to soil, reducing mobility, while shorter-chain PFAS are more mobile and influenced by SOM charge, which is affected by both pH and the type of cation present.

Plant Uptake and Bioaccumulation. Costello and Lee (2020) reviewed 50 studies on the uptake of per- and polyfluoroalkyl substances (PFAS) in agricultural plants. These studies employed hydroponic (n = 17), pot (n = 19), and field (n = 14) methods, encompassing 63 different crop types. Grains, leafy vegetables, and root vegetables were the most frequently studied crops, whereas fruits were the least examined. In general, vegetative plant components exhibited higher PFAS concentrations than fruits and grains. Notably, floret vegetables grown in home gardens showed elevated PFAS levels (Scher et al., 2018). The chain length of PFAS compounds significantly affects their behavior in soil and plants—long-chain perfluoroalkyl acids (PFAAs) tend to be less mobile and bioavailable compared to short-chain alternatives (Muñoz et al., 2019; Choi et al., 2019).

Comparative analysis of PFAS uptake is challenging due to variability across plant species, cultivars, and plant components, as well as inconsistencies in data reporting—such as the use of wet versus dry weight (Ghisi et al., 2019). Several key metrics are commonly used to assess PFAS distribution in plants: root concentration factor (RCF), translocation factor (TF), shoot concentration factor (SCF), bioconcentration factor (BCF), and the less frequently used transpiration stream concentration factor (TSCF), which is most applicable in hydroponic studies (Sharma et al., 2020). The physicochemical properties of PFAS—particularly chain length and functional group—consistently influence RCFs and TFs. In general, RCFs increase with chain length and are higher for perfluoroalkane sulfonic acids (PFSAs) than for perfluoroalkyl carboxylic acids (PFCAs) of similar length. Conversely, TFs tend to increase as chain length decreases (Liu et al., 2019; Zhang et al., 2019; Zhao et al., 2016).

The bioaccumulation factor (BAF) for PFAS varies not only between plant species but also among different plant tissues within the same species. For instance, in celery, the root exhibited a BAF of 133.46 for perfluorobutanoic acid (PFBA), calculated from a root concentration of 517.84 µg/kg and an initial soil concentration of 3.88 mg/kg (Liu et al., 2019). In contrast, the leaf blade of celery showed a nearly two-fold higher BAF of 270.52, based on a plant concentration of 1049.61 µg/kg and the same soil concentration. Among plant groups where BAFs were reported (carrot, Welsh onion, celery, and radish), the ranking of tissue-specific BAFs from highest to lowest was: leaf > root > flower > shoot. Overall, PFAS concentrations in plants increased with higher PFAS levels in soil (Xu et al., 2022).

Study design plays a critical role in shaping PFAS uptake outcomes. Hydroponic systems offer high PFAS bioavailability but may restrict root development, thereby reducing the root surface area available for uptake (Gredelj et al., 2020). Pot studies typically begin with seedlings, omitting potential PFAS effects on germination, and prevent leaching—resulting in the retention of short-chain PFAS within the root zone. In contrast, field studies account for a broader range of environmental variables, including climate, soil heterogeneity, and leaching, making them more representative of real-world conditions. For example, short-chain PFAS were observed to leach from soil over the course of a growing season in field settings but remained accessible in pot studies (Sepulvado et al., 2011; Gredelj et al., 2019). However, field data remain limited, particularly for non-edible plant components. Additionally, atmospheric deposition—especially near industrial sites—can further confound interpretation of PFAS concentrations in plant tissues (Liu et al., 2019).

Few studies have investigated the uptake of alternative PFAS classes or precursor degradation intermediates. For example, Lin et al. (2020) reported that chlorinated polyfluoroalkylether sulfonates (Cl-PFAESs) in wheat exhibit chain length–dependent uptake patterns similar to those observed for PFCAs and PFSAs. Ultra-short-chain PFCAs (C2 and C3) have also demonstrated high uptake and mobility in hydroponically grown wheat (Zhang et al., 2019). Studies on PFAS precursors suggest that degradation products, such as PFOS, can accumulate in plant tissues; however, these findings may be confounded by the presence of precursor impurities (Zhao et al., 2018). In some cases, degradation appears to be driven by interactions with plant exudates rather than internal metabolic processes, as observed with 8:2 diPAP in carrots (Bizkarguenaga et al., 2016). Overall, plant-mediated degradation pathways and the influence of precursor impurities introduce additional complexity to understanding PFAS uptake mechanisms.

Evidence of presence in packaging, and the likelihood of transfer from packaging to the finished product. PFAS were widely used in the manufacture of food-contact materials. Due to their resistance to grease, oil, and water, PFAS have been applied as coatings on paper-based food packaging (fast-food wrappers, microwavable popcorn bags, take-out containers, and some other types of packaging).

Empirical research consistently shows that PFAS (per- and polyfluoroalkyl substances) can migrate from food-contact materials into food, but this migration varies significantly depending on factors, such as food composition (particularly fat content), temperature, contact duration, and the chemical structure of the PFAS. Two studies by Begley et al. (2005, 2008) and others demonstrated significant migration into high-fat foods like butter and popcorn, especially at elevated temperatures and in the presence of emulsifiers. Additional variables influencing PFAS migration include pH, salt, and moisture content, as shown in studies by AbulFadl et al. (2019), Fengler et al. (2011), and Zabaleta et al. (2020). Reusable cookware was found to contribute more persistent contamination than single-use items due to cumulative exposure. Phelps et al. (2024), using the FCCmigex database, identified 68 PFAS compounds in food-contact materials, mostly PFCAs and fluorotelomer-based substances, with paper and board packaging being the most common sources. The predominance of targeted analytical methods in PFAS detection raises concerns about underreporting less common or unidentified compounds, suggesting current surveillance may underestimate actual PFAS presence.

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