

# Per- and polyfluoroalkyl substances in irrigated agricultural systems: sources, environmental fate, crop uptake, human health risks, and mitigation strategies

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## Abstract

Per- and polyfluoroalkyl substances (PFAS) are persistent contaminants that are increasingly of concern in irrigation farming systems because they can enter the soil, water, plants, sediments, groundwater, and food chains. This review synthesizes current evidence on PFAS sources, transport pathways, environmental fate, crop uptake, food-chain exposure, and mitigation strategies in irrigated agricultural systems, with emphasis on the soil–water–crop–groundwater continuum. The literature was obtained from the Scopus database with the keyword "PFAS irrigation agriculture" and produced 43 documents, consisting of 40 articles and 3 reviews. The results of the study show that the main sources of PFAS on agricultural land include polluted irrigation water, treated wastewater, reclaimed water, biosolids, biosolid-based compost, pesticides, agricultural plastics, atmospheric deposition, landfills, wastewater treatment plants, polluted river water, and industrial emissions. PFAS can move through infiltration, leaching, runoff, drainage, groundwater transport, and sediment accumulation. Short-chain PFAS tend to be more mobile and easily move into water and plant tissues, while long-chain PFAS are more strongly bound to soil, roots, and sediments. Some crops such as rice, soybeans, wheat, tomatoes, lettuce, turnips, and feed crops can accumulate PFAS through root uptake and, under certain conditions, foliar uptake. Health risks are mainly related to the consumption of agricultural products and animal food from polluted systems. Mitigation strategies include water source management, alternating irrigation, biochar, carbon adsorbents, soil remediation, validation of analytical methods, and transport modeling. This review emphasizes the need for a soil-water-crop-groundwater continuum approach for integrated PFAS management.

## KEYWORDS

PFAS; irrigation; agriculture; crop uptake; food safety; mitigation.

## 1. INTRODUCTION

Per- and polyfluoroalkyl substances (PFAS) are a group of synthetic compounds that are widely used in industrial and commercial products due to their stable properties to heat, water, oil, and chemical degradation (Gaines, 2023; Glüge et al., 2020). This stable property makes PFAS difficult to decompose in the environment (Dhore & Murthy, 2021). Because of this, PFAS are often referred to as persistent contaminants. These compounds can survive for a long time in a variety of environmental matrices, including water, soil, sediment, groundwater, and living organisms (Ismanto et al., 2026). Several studies show that PFAS are not only found in industrial areas, but also begin to be detected in agricultural systems and agroecosystems (H. Chen, Chow, Williams, Wang, & Sun, 2025; Verley, McLennon, Rein, Dikgang, & Kankarla, 2025). This is important because agricultural land is a space for food production that is directly related to human health and ecosystems (Anas et al., 2026).

In the context of agriculture, PFAS can enter the land through various routes. Frequently reported sources include polluted irrigation water, treated wastewater, reclaimed water, biosolids, waste-based compost, pesticides, agricultural plastics, atmospheric deposition, landfills, and industrial emissions (Renella, Carletti, & Masi, 2025). Irrigation water is one of the main pathways because it can carry PFAS directly into the soil, then move into groundwater or be absorbed by plants. L. Wang et al. (2026) reported that irrigation water is the main measurable source of PFAS in greenhouse soils and open land in China. Other studies have also shown that the use of treated wastewater and reclaimed water for irrigation can introduce PFAS into agroecosystems, especially through the relationship between water, soil, plants, and groundwater.

The presence of PFAS in agricultural land is a concern because these compounds can move across media. PFAS can infiltrate into the soil, travel to groundwater, transport through runoff and drainage, and accumulate in sediment (Borthakur et al., 2021). Short-chain PFAS are generally more mobile and

move more easily through water, while long-chain PFAS are more strongly retained in soil, roots, and sediment (Z. Li, Hui, Li, Li, & Liu, 2026). In rice field systems, changes in water conditions such as inundation, drought, and rehydration can affect the release of PFAS at the ground-water interface (Huang et al., 2025). This suggests that the fate of PFAS in agriculture is determined not only by their source, but also by the nature of the soil, irrigation patterns, redox conditions, and the character of the compound (Costello & Lee, 2024).

Although research on PFAS in agriculture continues to increase, scientific evidence on sources, transportation, crop accumulation, health risks, and mitigation is still scattered across a wide range of commodities, locations, methods, and environmental matrices. Some studies focus on irrigation water and groundwater, while others discuss soils, crops, sediments, biochar, or risk models. This condition shows the need for a more targeted synthesis of irrigation-based agricultural systems. This review aims to synthesize scientific evidence on the source, transportation, plant accumulation, health risks, and PFAS mitigation strategies in irrigation-based farming systems.

## 2. REVIEW METHODOLOGY

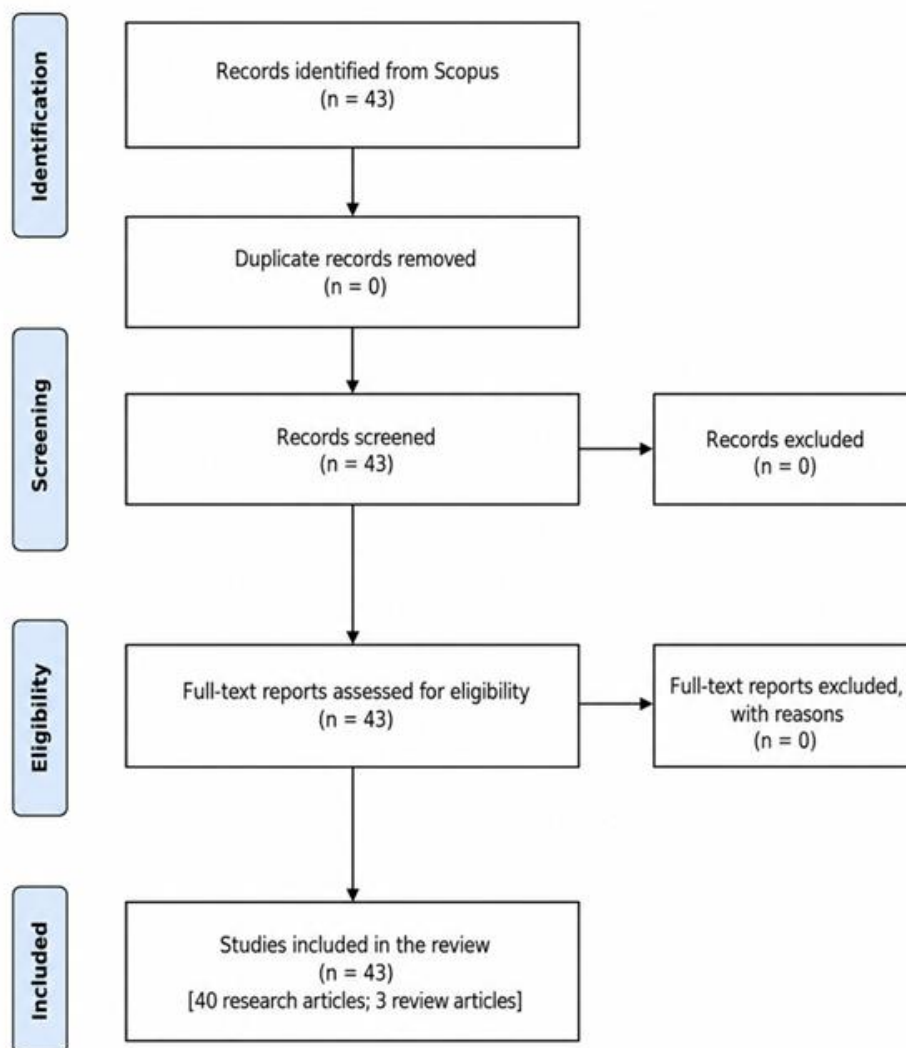
This review was conducted using a structured literature review approach to synthesize current evidence on per- and polyfluoroalkyl substances (PFAS) in irrigated agricultural systems. The literature search was carried out using the Scopus database with the keyword combination “PFAS irrigation agriculture”. Scopus was selected because it provides broad coverage of peer-reviewed international publications relevant to environmental science, agriculture, water management, and food safety.

The search identified 43 documents, consisting of 40 research articles and 3 review articles. The selection process followed the logic of the PRISMA 2020 flow diagram (Figure 1). Since the search was conducted using a single database, no duplicate records were removed. All 43 records were screened

based on title, abstract, and relevance to the review scope. The eligibility criteria included studies discussing PFAS sources, transport pathways, environmental fate, crop uptake, food-chain exposure, human health risks, or mitigation strategies in agricultural, irrigation, soil, water, groundwater, sediment, or crop systems. Documents unrelated to PFAS, irrigation, agriculture, or the soil–water–crop–groundwater continuum were excluded.

Data from the selected documents were extracted and synthesized thematically according to

five main topics: sources of PFAS entering agricultural land, transport and fate in soil–water–sediment systems, uptake and accumulation in crops, implications for food safety and human health, and mitigation strategies. A qualitative narrative synthesis was used because the included studies varied in terms of research design, location, environmental matrix, PFAS compounds analyzed, crop species, and risk assessment methods. Therefore, this review emphasizes an integrated soil–water–crop–groundwater continuum framework rather than a quantitative meta-analysis.



**Figure 1.** PRISMA flow diagram of the literature selection process

**Table 1.** Sources of PFAS Entering Agricultural Land

Source of PFAS	Entrance to farmland	Key findings	Reference
Irrigation water	PFAS are carried through irrigation water into soil, crops, and groundwater	Irrigation water is the main measurable source of PFAS in greenhouses and open land in China. The contribution is 20.1% to greenhouses and 31.4% to open land	(L. Wang et al., 2026)
Treated Wastewater	Treated wastewater used for crop irrigation	Treated wastewater can carry PFAS into soil systems, crops, and the food chain	(Kosiarski, Usner, & Preisendanz, 2025; Shi et al., 2025; Simonetti et al., 2026)
Reclaimed water	Reclaimed water is used as an irrigation source	Reclaimed water becomes a non-point source of PFAS in shallow groundwater in irrigation areas	(Szabo, Coggan, Robson, Currell, & Clarke, 2018; Xingchun et al., 2023)
Biosolids or sewage sludge	Biosolids are applied to the soil as soil improvers or organic fertilizers	Biosolids contain PFAS and can cause PFAS residues in surface soils, deep soil layers, and groundwater	(Johnson, 2022; Pepper, Brusseau, Prevatt, & Escobar, 2021)
Biosolid-based compost	Compost from biosolids is used as soil amendment	PFHxA is more protected from biosolid-based compost than any other treatment	(Levine, Bean, Hinz, Wilson, & Reisinger, 2023)
Pesticides	Certain pesticides can contain or carry PFAS compounds	Pesticides are cited as one of the potential sources of PFAS in agricultural soils	(Biswas et al., 2025; Preisendanz, Li, Mashtare, & Mina, 2025; L. Wang et al., 2026)
Agricultural plastics	Mulch film and agricultural plastic products go into the soil	Plastic products such as agricultural films are a potential source of PFAS in agricultural land	(L. Wang et al., 2026)
Fluorochemical industry	Industrial emissions enter through air, water, soil, or groundwater	Fluorochemical, textile, food packaging, and related industries are sources of PFAS in soils and food crops	(Bao et al., 2019; B. Li et al., 2025; Xing et al., 2024)

Atmospheric deposition	PFAS from air fall into the soil or plant surface	Air deposition acts as a source of PFAS in wheat systems near fluorochemical industrial estates	(X. Chen et al., 2024)
Landfill and wastewater treatment plants (WWTP)	Landfill leachate and wastewater treatment plant effluent entering aquifers or land	Landfills, wastewater treatment plants, and recycled water irrigation are potential sources of PFAS in coastal aquifers	(Jones et al., 2026)
Polluted rivers or surface water	River water is used for irrigation or receives agricultural runoff	PFAS are found in rivers affected by agricultural, industrial, and urbanization activities	(Madeira et al., 2023; McDonough, Bird, Freeman, Luciani, & Todd, 2021; Shigei, Ahrens, Hazaymeh, & Dalahmeh, 2020);
Industrial waste incineration	Emissions from burning waste enter the soil around agricultural land	Burning of high-calorie industrial waste in brick kilns identified as a new source of PFAS emissions to farmland	(Baqar et al., 2024)

**Table 2.** Transport and Fate of PFAS in Soil, Water, and Sediment

Compartments	Transport process or fate of PFAS	Key findings	Reference
Agricultural land	Accumulation in the soil due to irrigation	Rice paddies have higher concentrations of PFAS than drylands, likely due to accumulation triggered by irrigation	(B. Li et al., 2025)
Soil and water irrigation	Transfer from irrigation water to soil and plant tissues	In rice field systems, PFAS are found in irrigation water, soil, roots, stems, leaves, and grain	(B. Li et al., 2025)
Rice paddies	PFAS release at the soil-water interface after drought	Post-drought rehydration increases the release of short-chain PFAS into surface water in rice fields	(Wu et al., 2025)
Flooded rice fields	Effects of nitrogen-iron redox	Irrigation conditions change the nitrogen-iron redox, dissolved organic matter (DOM), and extracellular polymeric substances (EPS). This process affects the migration of PFAS at the water-soil interface	(Wu et al., 2025)

Irrigation and drainage channels	PFAS move from irrigation water to drainage and receiving lakes	The concentration of PFAA increases from irrigation water to drainage water and receiving lakes. PFOA shows the strongest increase	(M. Zhang et al., 2021)
Groundwater aquifers	Movement of PFAS from surface sources to groundwater	PFAS are detected in coastal aquifers. Suspected sources include landfill, WWTP, and recycled water irrigation	(Jones et al., 2026)
Shallow and deep groundwater	Influence of well depth	PFAS are higher in shallow aquifers and lower in deep aquifers. Reclaimed water irrigation is the main source of shallow groundwater	(Xingchun et al., 2023)
Groundwater in the reuse water area	Recycled water as a diffuse source	PFAS detected in 100% of groundwater samples at recycled water irrigation sites in Melbourne	(Szabo et al., 2018)
Vadose zone	Adsorption at the air-water interface	The LEACHM and HYDRUS-1D models are better at predicting PFOS and PFOA retention because they include adsorption at the air-water interface	(Liao et al., 2025)
Soil with biosolids	Vertical migration to deep soil	PFOA and PFOS can migrate to deeper layers of soil and are detected in groundwater underneath	(Johnson, 2022)
Soils with long-term biosolid applications	Attenuation with depth	The total concentration of PFAS decreases with depth. Average attenuation reaches 73% at a depth of 183 cm	(Pepper et al., 2021)
Andosol rice field lysimeter	Retention and rotation based on carbon chains	PFHxS and PFOS are highly retained in the low-humus Andosol layer. The distribution of PFAS is influenced by soil properties and carbon chain length	(Eun et al., 2022)
Lake sediments	Accumulation of PFAS in sediment	PFAS are detected in the sediments of urban lakes. PFBS shows an indication of substitution from PFOS	(H. Zhang et al., 2024)
Ponds and irrigation ditches	Transportation from biosolid land to water bodies	Trenches serve as PFAS transport routes. Long-chain PFAS are more trapped in the soil, while short-chain ones are more mobile	(Omagamre, Bala, Zebelo, & Pitula, 2025)

**Table 3.** PFAS absorption and accumulation in plants

Crops or commodities	PFAS entry routes	Key findings	Reference
Rice	Roots absorb PFAS from irrigation water and rice field soil	The order of concentration of PFAS in rice tissues is the root > stem > leaves > grain	(B. Li et al., 2025)
Rice on andosol lysimeter	Contaminated irrigation water enters the soil-rice system	The distribution of PFAS is influenced by soil adsorption, the mobility of compounds, the length of the carbon chain, and the functional group	(Eun et al., 2022)
Soybeans	Irrigation with a mixture of 10 PFAS	PFBAAs are dominant in soybeans, while long-chain PFAS are more retained at the roots	(Omagamre et al., 2025)
Wheat	Root and foliar uptake absorption	Spray irrigation increases the absorption of PFAS through leaves compared to flood irrigation. Foliar PFOA uptake is estimated to contribute about 25%	(X. Chen et al., 2024)
Tomatoes	PFAS-contaminated groundwater and contaminated soil	All tomato varieties accumulate PFAS on the leaves and fruits. Fruit mainly contains C4, C5, and C6 carboxylate PFAS	(Battisti et al., 2024)
Lettuce, radishes and tomatoes	Irrigation with treated wastewater	PFAS are still absorbed by plant tissues even though PFAS concentrations in treated wastewater are relatively low	(Shi et al., 2025)
Rocket plant	Treated municipal wastewater	Irrigation with reclaimed municipal wastewater causes the accumulation of 23 analytes in the rocket plant	(Seelig, Junghans, Reemtsma, & Zahn, 2025)
Corn and orchard grass	Treated wastewater irrigation	Root uptake becomes the dominant path. Foliar sorption is not a major contributor to plant tissues	(Kosiarski et al., 2025)
Corn and tall fescue	Long-term wastewater irrigation spray	More than 84% of PFAS in animal feed crops are short-chain compounds	(Mroczko et al., 2022)

Tomatoes, lettuce and beets	River water contaminated with low levels of PFAS	PFAS can transfer to plants, soil, and leachate. Short-chain PFAS are easier to transfer to plant organs	(McDonough et al., 2021)
Homemade vegetables and eggs	Irrigation or groundwater supply near the fluorochemical industry	PFBA and PFBS are the main contaminants in vegetables and homemade eggs	(Bao et al., 2019)
Variety of food crops	Roots, upper tissues, and edible parts	Important factors that affect uptake are chain length, functional group, solubility, volatility, plant physiology, pH, salinity, temperature, and soil organic matter	(Song, Gu, Zhang, Zhou, & Cui, 2024; W. Wang, Rhodes, Ge, Yu, & Li, 2020)

**Table 4.** Human Health Risk and Food Safety

Exposure pathway	Risk target	Main findings	Reference
Consumption of salad irrigated with reclaimed wastewater	PFOA exposure	The Bayesian model showed a low risk of PFOA exposure based on one-year monitoring data. However, this model is useful for decision-making in water reuse management	Simonetti et al., 2026
Consumption of PFAS-contaminated vegetables	Children and adults	The highest exposure was estimated in children aged 1 to 2 years. Vegetable consumption from PFAS-impacted irrigation water is an important exposure pathway	Brown et al., 2020
Consumption of tomatoes from contaminated sites	Human consumers	The hazard index in tomatoes from the most vigorous rootstock was slightly above 1, indicating a potential human health risk	Battisti et al., 2024
Consumption of soybeans	PFAS exposure through soybean grains	PFAS concentrations in soybean grains may contribute to exceeding the EFSA tolerable weekly intake	Omagamre et al., 2025
Consumption of animal products from contaminated forage	Livestock and humans	Forage crops can transfer PFAS to livestock and may further contribute to human exposure through animal-derived food products	Kosiarski et al., 2025
Consumption of aquatic food	Communities around irrigation	Estimated daily intake of PFOA, perfluorononanoic acid (PFNA), perfluorohexane sulfonic acid (PFHxS), and	Zhang et al., 2021

	and drainage systems	PFOS through aquatic food consumption reached 6 to 42% of the tolerable daily intake in urban populations	
Groundwater use and consumption of home-produced vegetables	Residents near fluorochemical industrial areas	PFBA, PFOA, and PFBS concentrations in groundwater were significantly associated with their levels in home-produced vegetables	Bao et al., 2019
Rice consumption from paddy field systems	Human consumers	The measured PFAS levels were not considered to pose a significant human health risk. However, PFAS alternatives still require attention for food safety	Li et al., 2025
Consumption of rocket plants irrigated with reclaimed wastewater	General consumers	No critical exposure was identified under normal consumption levels based on the toxicological threshold approach	Seelig et al., 2025
Consumption of crops from wastewater-irrigated farmland in Jordan	Food and feed consumers	PFAS levels in wastewater, surface water, and soil were relatively low. No PFAS accumulation was detected in alfalfa and mint plants	Shigei et al., 2020

### 3. SOURCES OF PFAS IN IRRIGATED AGRICULTURAL SYSTEMS

PFAS can enter farmland through several main pathways, especially irrigation water, treated wastewater, reclaimed water, biosolids, biosolid-based compost, and pesticides. Irrigation water is an important pathway because it can carry PFAS directly into soil, groundwater, and plant tissues (Table 1). In the study of L. Wang et al. (2026), irrigation water was reported as the main measurable source of PFAS in greenhouse soils and open land in China. The use of *treated wastewater* and *reclaimed water* is also a concern because both can carry PFAS from wastewater treatment plants to agricultural systems (Simonetti et al., 2026). Some studies show that treated wastewater can increase PFAS exposure to soils, food crops, shallow groundwater, and the food chain (Kosiarski et al., 2025). In addition, the application of biosolids and biosolid-based compost as soil enhancers can be a source of PFAS because these compounds can be

left on surface soil, move into deeper soil layers, or be coated into groundwater. Pesticides are also referred to as potential sources of PFAS because some agricultural materials can contain fluorinated compounds or PFAS precursors (Biswas et al., 2025).

*In addition, the application of biosolids and biosolid-based compost as soil enhancers can be a source of PFAS because these compounds can be left on surface soil, move into deeper soil layers, or be coated into groundwater*

Other sources that are also important are agricultural plastics, the fluorochemical industry, atmospheric deposition, landfills, WWTP, polluted river water, and industrial waste incineration. Agricultural plastics such as mulch or *agricultural films* can be a source of PFAS residues in soil, especially in intensive farming systems (L. Wang et

al., 2026). Fluorochemical, textile, and food packaging industry activities can release PFAS into the air, water, soil, and groundwater, and then enter land through irrigation or deposition. Atmospheric deposition also plays a role, especially on land near industrial estates, as PFAS from the air can fall into the ground or stick to plant surfaces (Baqar et al., 2024). Landfills and *wastewater treatment plants* can contaminate aquifers and irrigation water through leachate or effluent. Rivers that receive agricultural, industrial, and urbanized runoff can also carry PFAS if used as an irrigation source. In addition, the burning of industrial waste in brick kilns around farmland was identified as a new source of PFAS emissions to farmland (Madeira et al., 2023)

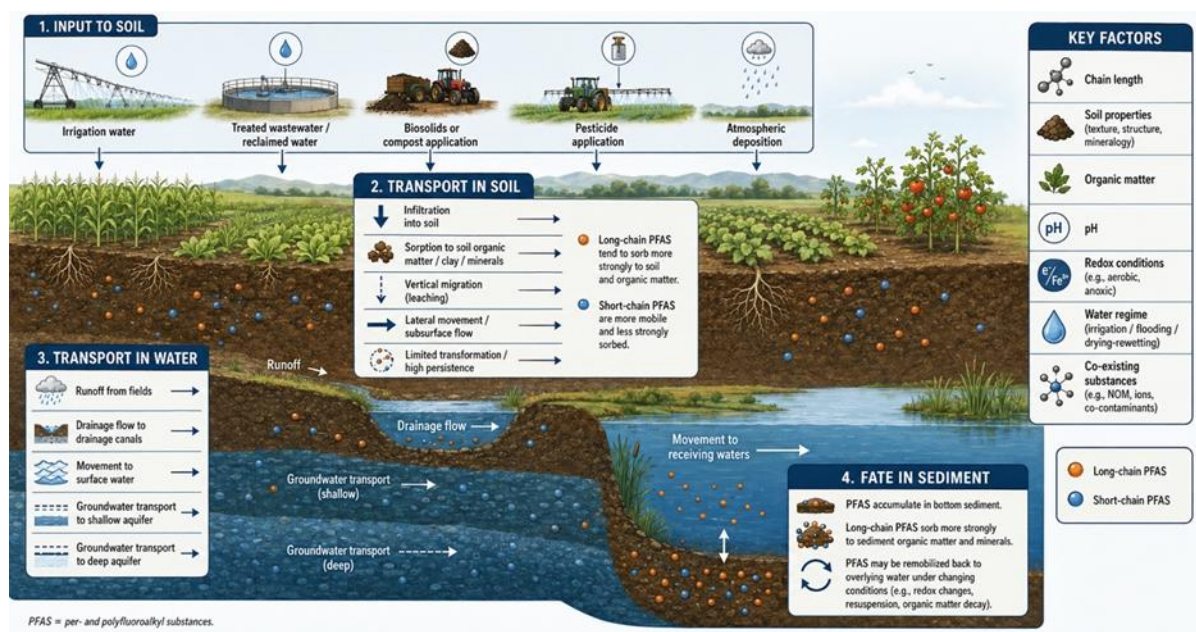
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#### **4. TRANSPORT AND ENVIRONMENTAL FATE**

The transport and fate of PFAS in agricultural environments is strongly influenced by irrigation water, soil properties, carbon chain lengths, redox conditions, and wet-dry dynamics. In agricultural soils, PFAS can move from irrigation water to soil, then enter plant tissues or move deeper into vadose and groundwater zones ([Table 2](#) and [Figure 2](#)). The study by B. Li et al. (2025) shows that rice systems tend to have higher PFAS accumulation than dry

land due to the influence of irrigation. In rice, PFAS are found in irrigation water, soil, roots, stems, leaves, and grain. Wu et al. (2025) also explain that rehydration after drought can increase the release of short-chain PFAS from soil to rice field surface water. This suggests that PFAS do not always settle in the soil, but can be released back when water conditions change. Wu, Li, Chen, Liu, and Tu (2024) added that the redox processes of nitrogen-iron, dissolved organic matter, and extracellular polymeric substances help regulate the transfer of PFAS at the water-soil interface.

In water systems, PFAS can move from irrigation water into drainage channels, receiving lakes, shallow groundwater, deep groundwater, and coastal aquifers. M. Zhang et al. (2021) reported that perfluoroalkyl acids (PFAAs) concentrations increased from irrigation water to drainage water and receiving lakes, with PFOA as the compound showing the most potent increase. Xingchun et al. (2023) found that PFAS were higher in shallow aquifers and decreased in deep aquifers, while Szabo et al. (2018) showed that recycled water for irrigation can be a diffuse source of PFAS into groundwater. In soils that receive biosolids, Johnson (2022) and Pepper et al. (2021) show that PFAS can migrate vertically, although their concentrations decrease with depth. In sediments, H. Zhang et al. (2024) found PFAS in urban lake sediments, with perfluorobutanesulfonic acid (PFBS) as an indication of perfluorooctanesulfonic acid (PFOS) substitutes. In general, short-chain PFAS move more easily in water and soil, while long-chain PFAS are more retained in soil or sediment.



**Figure 2.** Transport pathways of PFAS in irrigated agricultural systems

## 5. CROP UPTAKE AND BIOACCUMULATION

PFAS uptake and accumulation in plants mainly occur through root uptake from contaminated irrigation water, soil, wastewater, reclaimed water, biosolids, and polluted groundwater (Table 3). Several crops can absorb PFAS, including rice, soybean, wheat, tomato, lettuce, radish, rocket plant, corn, orchard grass, and forage crops. In paddy systems, PFAS can move from irrigation water and soil into rice tissues, with higher accumulation usually found in roots than in aboveground tissues. Soybean studies show that short-chain PFAS, especially PFBA, can dominate in beans, while long-chain PFAS tend to remain in roots (Omagamre et al., 2025). Tomato studies also show PFAS accumulation in leaves and fruits, especially short-chain carboxylic PFAS such as C4, C5, and C6 compounds (Battisti et al., 2024).

*Several crops can absorb PFAS, including rice, soybean, wheat, tomato, lettuce, radish, rocket plant, corn, orchard grass, and forage crops. In paddy systems, PFAS can move from irrigation water and soil*

*into rice tissues, with higher accumulation usually found in roots than in aboveground tissues*

The level of PFAS accumulation depends on PFAS chain length, functional group, water solubility, plant species, root system, transpiration, soil organic matter, pH, salinity, temperature, and irrigation method. Short-chain PFAS are usually more mobile and more easily transported to edible tissues, while long-chain PFAS show stronger retention in roots, soil, or sediment. Root uptake is the dominant pathway in most agricultural crops, but foliar uptake can also contribute, especially near industrial sources or under spray irrigation (Kosiarski et al., 2025). Studies on rocket plant, lettuce, radish, tomato, corn, and forage crops confirm that wastewater reuse can introduce PFAS into edible or feed tissues, even when PFAS concentrations in irrigation water are relatively low (Mroczko et al., 2022). Therefore, PFAS uptake by plants becomes an important link between contaminated irrigation systems and food safety risk.

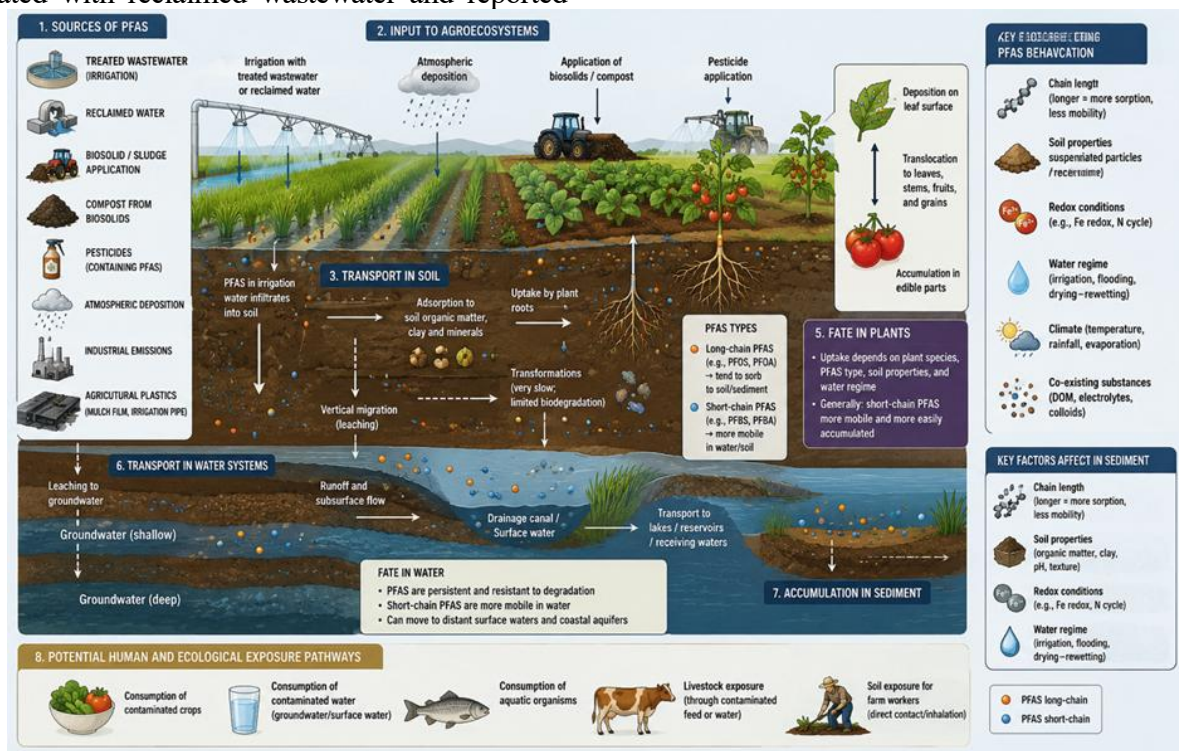
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### 6. HUMAN HEALTH RISK AND FOOD SAFETY

Table 4 and Figure 3 show that PFAS-related health risk in irrigated agriculture mainly occurs through the food chain, especially when contaminated irrigation water, reclaimed wastewater, groundwater, or soil transfers PFAS into edible crops. Simonetti et al. (2026) used a Bayesian risk model for PFOA exposure from salad irrigated with reclaimed wastewater and reported

low exposure risk in the monitored case, but the study still highlights the need for risk-based water reuse management. Brown, Conder, Arblaster, and Higgins (2020) showed that vegetable consumption can become an important PFAS exposure pathway, especially for young children aged 1 to 2 years. Several crop-specific studies also support this concern. Omagamre et al. (2025) found that PFAS in soybean grains could contribute to exceeding the EFSA tolerable weekly intake, while Battisti et al. (2024) reported a hazard index slightly above 1 in tomatoes grown at a contaminated site, indicating possible health risk for consumers.

*used a Bayesian risk model for PFOA exposure from salad irrigated with reclaimed wastewater and reported low exposure risk in the monitored case, but the study still highlights the need for risk-based water reuse management. Brown, Conder, Arblaster, and Higgins*



**Figure 3.** Sources, fate, transport, and exposure pathways of PFAS in agricultural systems

The table also shows that PFAS exposure is not limited to direct vegetable consumption. Kosiarski et al. (2025) showed that wastewater-irrigated forage crops can transfer PFAS to livestock, which may create an indirect pathway to humans through animal-derived foods. M. Zhang et al. (2021) reported that PFAS exposure through aquatic food from irrigation and drainage systems could account for 6 to 42% of the strictest tolerable daily intake in urban populations. Bao et al. (2019) found significant links between PFAS levels in groundwater and home-produced vegetables near a fluorochemical industrial area. However, not all studies reported high risk. B. Li et al. (2025) found that PFAS levels in rice did not pose a significant current health risk, although PFAS alternatives still require attention. Seelig et al. (2025) found no critical exposure from rocket plants under normal consumption levels, and Shigei et al. (2020) reported low PFAS levels in wastewater-irrigated farmland in Jordan with no PFAS accumulation in alfalfa and mint.

## 7. MITIGATION AND MANAGEMENT STRATEGIES

PFAS mitigation strategies in irrigated farming systems can be carried out through the regulation of water sources and irrigation patterns. The use of treated wastewater or reclaimed wastewater does support water efficiency, but it can also bring PFAS into soil, plants, and the food chain. Therefore, the alternating irrigation strategy is a practical approach. Shi et al. (2024) showed that the use of treated wastewater at the beginning of last season replaced with clean water in the middle of the season can reduce the accumulation of contaminants in edible plant tissues. Shi et al. (2025) also reported that replacing treated wastewater with clean water in radishes, lettuce, and tomatoes was able to reduce the accumulation of contaminants by up to 82.4%, including persistent PFAS. In rice field systems, water management is also important because flood, drought, and rehydration conditions can alter the mobility of PFAS. Wu et al. (2025) explain that

irrigation affects the redox processes of nitrogen-iron, dissolved organic matter, and PFAS migration at the soil-water interface. Wu et al. (2025) added that rehydration after drought can increase the release of short-chain PFAS into rice field surface water.

In addition to water management, PFAS removal can also be done by carbon adsorbents, biochar, soil remediation, laboratory method validation, and transport modeling. Papes, Shimabuku, Garbowski, and Kennedy (2025) showed that powdered bone char and halophyte biochar can remove PFAS from brackish irrigation water, although the doses are higher than that of activated carbon. Ramos and Ashworth (2024) explain that biochar can be used for water filtration, direct application to soil, or mixing with biosolids, with effectiveness influenced by surface area, porosity, and physicochemical properties of biochar. Yamashita, Yamazaki, Taniyasu, Hanari, and Yeung (2024) highlight the potential for activated carbon from rice husks as PFAS adsorbents in rice farming systems. For polluted soils, Biswas et al. (2025) mentioned that remediation can include physical, chemical, and biological approaches. However, Zheng et al. (2025) emphasize that adsorption tests should be careful because the use of filter syringes can overestimate the efficiency of PFAS removal. Liao et al. (2025) also show that the LEACHM and HYDRUS-1D models can help predict long-term PFAS runoff, especially if the model incorporates unsaturated water flow and adsorption at the air-water interface.

## 8. FUTURE CHALLENGES AND RECOMMENDATIONS

The main research gap in the study of PFAS in irrigated agriculture lies in the limitations of long-term field data, especially those that monitor the relationship between irrigation water, soil, crops, sediments, and groundwater simultaneously. Many studies are still based on greenhouse experiments, pot experiments, simulations, or specific locations,

so the results are not fully representative of real farmland conditions in the long term. Liao et al. (2025) emphasize the importance of transport models such as LEACHM and HYDRUS-1D for predicting PFAS runoff in soil profiles, but these models still require field validation. Mroczko et al. (2022) show that long-term wastewater utilization can affect groundwater quality and plant tissues, while Johnson (2022) shows that historical biosolid applications can leave PFAS in soil and groundwater. Therefore, the direction of the review needs to emphasize the soil-water-crop-groundwater continuum framework, so that the transfer of PFAS from irrigation sources to crops and groundwater can be explained systematically.

Another gap is in the understanding of short-chain PFAS, emerging PFAS, plant uptake pathways, food risk, and mitigation effectiveness. B. Li et al. (2025) and Xing et al. (2024) show that emerging PFAS and short-chain PFAS are beginning to be found in soil and plants, but their behavior, toxicity, and risk priority are not yet fully clear. In plants, Kosiarski et al. (2025) show that root uptake becomes the main pathway in feed crops, while X. Chen et al. (2024) show that foliar uptake can also occur, especially in areas near industrial or spray irrigation systems. This shows that the review needs to distinguish the mechanisms of root uptake, foliar uptake, translocation, and bioaccumulation factors. Food risks are also not uniform between commodities, as some studies show low risks, while others have found potential risks in vegetables, soybeans, tomatoes, or feed crops. On the mitigation side, biochar and carbon adsorbents are promising, but Papes et al. (2025), Ramos and Ashworth (2024), and Yamashita et al. (2024) show that their effectiveness is still influenced by the material character, dosage, cost, and readiness of field applications. In addition, Zheng et al. (2025) assert that laboratory methods can be biased if the filtration process makes the PFAS removal efficiency appear higher than the actual conditions. Therefore, a strong review direction needs to incorporate discussions on sources, transportation, plant uptake,

food risk, method validation, and field-based mitigation strategies.

## 9. CONCLUSION

This study highlights that PFAS can enter agricultural systems through multiple pathways, including irrigation water, treated wastewater, reclaimed water, biosolids, pesticides, agricultural plastics, atmospheric deposition, industrial emissions, landfills, WWTPs, and polluted rivers. Among these, irrigation water is a critical pathway because it directly links contamination sources to soil, crops, groundwater, and the food chain. PFAS behavior in agroecosystems is complex, as these compounds can persist in soil, migrate to groundwater, accumulate in sediments, and be absorbed by plants. Short-chain PFAS are generally more mobile and easily transferred to water and plant tissues, while long-chain PFAS tend to remain in soil, roots, and sediments.

Plant uptake of PFAS is a major concern for food safety, as studies have reported PFAS accumulation in crops such as rice, wheat, soybeans, lettuce, tomatoes, radishes, corn, and feed crops. This creates potential health risks, particularly for children, vegetable consumers, and communities using contaminated groundwater or irrigation water. Therefore, PFAS management in agriculture requires integrated strategies, including safer water source regulation, biosolid control, groundwater monitoring, soil remediation, carbon adsorbents, biochar application, and transport modeling. However, mitigation technologies still need field-scale validation and reliable laboratory assessment. Future research should focus on long-term field studies, emerging PFAS monitoring, crop-specific risk comparison, mitigation technology validation, and safer policies for irrigation water and biosolid use. A soil-water-crop-groundwater continuum approach is essential to understand PFAS sources, transport, accumulation, risks, and control in agricultural systems.

## CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Zhulvie Meylanzharie: Writing – original draft, Conceptualization. Iswahyudi Iswahyudi: Conceptualization, Supervision, Writing – review & editing. Zakiyatuz Zhulva Nabila Wahyudi: Validation, Resources. Muhammad Ilman Wahyudi: Data Curation, Writing - Review & Editing, Visualization.

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No ethical approval was needed for this study.

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## CONFLICT OF INTEREST

The authors declares no conflicts of interest.

## DATA AVAILABILITY STATEMENT

Data available by request

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