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Mapping PFAS behavior via meta-analysis of soil dynamics, predictive modeling and policy integration

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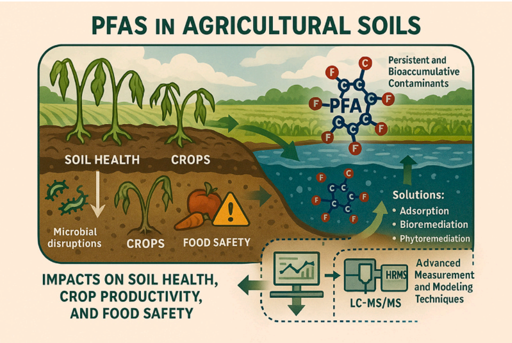
HIGHLIGHTS

- PFAS persist in soils, impacting health, crop productivity, and food safety.
- Advanced techniques improve PFAS measurement accuracy in agricultural soils.
- Modeling predicts PFAS mobility, aiding environmental risk assessments.
- Remediation methods like bioremediation reduce PFAS contamination risks.
- Policy standardization is crucial for effective PFAS management in agriculture.

GRAPHICAL ABSTRACT



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ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) are persistent organic pollutants with increasing prevalence in agricultural soils, primarily introduced through biosolid application, wastewater irrigation, and atmospheric deposition. This review provides a meta-analysis of terminologies across 145 peer-reviewed studies, identifying inconsistency in the classification of PFAS subgroups—such as "long-chain vs. short-chain," "precursors," and "emerging PFAS"—which hinders regulatory harmonization and model calibration. Empirical data reveal PFAS leaching depths ranging from 3 cm in sandy soils under low irrigation (1500 ng/L) to 10 cm in clay under high irrigation (200 ng/L). Analytical advances, including LC-MS/MS and hyperspectral drone imaging, enable detection limits below 0.05 μg/kg and hotspot identification at 1 m spatial resolution. Modeling tools like HYDRUS, MODFLOW-MT3DMS, and CalTOX simulate PFAS transport, bioaccumulation, and degradation with increasing fidelity. Biochar application reduced PFOS leaching by >80 %, and plasma treatment achieved 95 % PFAS degradation within 2 h. A global policy comparison reveals fragmented regulatory frameworks: the U.S. EPA promotes voluntary monitoring and advisory levels (e.g., 4 ng/L for PFOA+PFOS in water), while the EU progresses toward enforceable soil thresholds and PFAS phase-outs under REACH. Austria's ÖNORM S 2088-2 integrates human, plant, and ecological endpoints, contrasting with the USDA's BMP (Best Management Practices)-driven mitigation. The review advocates for terminology standardization, integration of multi-model transport and fate simulations, and hybrid remediation strategies. Policy convergence, driven by data

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transparency and international scientific cooperation, is imperative to safeguard soil health, food safety, and ecological resilience in PFAS-impacted agroecosystems.

1. Introduction

PFAS are a group of synthetic chemicals widely used for their exceptional resistance to heat, water, and oil (Glüge et al., 2020). These properties have made PFAS essential in various industrial processes and consumer products, including non-stick cookware, waterproof clothing, food packaging, and firefighting foams (Glüge et al., 2020; McFarlan and Lemke, 2024). However, these same attributes render PFAS highly persistent in the environment, earning them the moniker "forever chemicals" (Diaz and Stewart, 2019). Their resistance to natural degradation processes has led to widespread contamination of soil, water, and air, posing significant challenges to environmental sustainability (Ambaye et al., 2022). Agricultural soils are particularly susceptible to PFAS contamination, as they act as a sink for various pollutants introduced through biosolids, irrigation, and atmospheric deposition (Sarkar et al., 2021). PFAS contamination in soils is concerning because of their mobility, which enables their transfer to groundwater and uptake by plants, potentially entering the food chain (Blaine et al., 2013). Their widespread presence and potential for bioaccumulation and toxicity make PFAS a pressing environmental and agricultural concern.

The contamination of agricultural soils with PFAS originates from multiple sources such as biosolids, sewage sludge, irrigation water, atmospheric deposition, treated wastewater effluent, firefighting foams, and industrial and municipal compost (Bolan et al., 2021). However, Biosolids, derived from municipal wastewater treatment plants, are a primary contributor (Seiple et al., 2017). These biosolids, often applied to fields as fertilizer, can contain significant concentrations of PFAS that accumulate in the soil over time (Marchuk et al., 2023). Similarly, irrigation with contaminated water introduces PFAS into agricultural systems, particularly in regions relying on surface or groundwater sources affected by industrial or municipal discharges (Ghisi et al., 2019). Table 1 summarizes the predicted leaching potential of PFAS under different irrigation scenarios and soil types. It shows that sandy soil with low irrigation has the highest leaching potential, while clay soil with high irrigation has the lowest. The addition of mulch in loamy sand under high irrigation reduces leaching potential to a moderate level. These findings highlight the importance of soil type and irrigation practices in managing PFAS contamination.

Meta-analysis of PFAS leaching studies indicates that soil pH, organic carbon content, texture, and PFAS molecular structure (e.g., chain length and functional groups) are critical factors influencing leaching behavior. Sorption mechanisms vary significantly across soil types and PFAS subgroups, affecting mobility and retention. Incorporating these variables into predictive models can improve accuracy and site-specific risk assessments. Based on findings from meta-analysis and established PFAS sorption mechanisms, it is essential to identify and quantify the key influencing factors that govern PFAS leaching behavior across diverse environmental contexts. Factors such as soil pH, organic carbon content, soil texture, and the molecular structure of PFAS compounds—including chain length, functional groups, and hydrophobicity—play critical roles in determining sorption affinity and mobility. By assigning contribution weights to these variables, the prediction model can be refined to account for compound-specific interactions and site-specific conditions. This approach enhances the model's accuracy and generalizability, enabling more reliable assessments of PFAS transport and environmental risk. PFAS sorption is governed not only by electrostatic interactions but also by air–water interfacial adsorption, especially in unsaturated soils. Molecular structure plays a pivotal role: long-chain PFAS exhibit stronger sorption due to increased hydrophobicity and molar volume, while short-chain PFAS show enhanced mobility and weaker retention, as demonstrated by Brusseau et al., 2020 through quantitative structure–property relationship (QSPR) modeling. Furthermore, machine learning models such as PFASorption ML have quantified the relative contribution of these factors, revealing that molecular weight, hydrophobicity, and organic carbon content are among the most influential variables for predicting solid–liquid distribution coefficients (Kd) (Bugsel et al., 2021). Incorporating these weighted parameters into leaching models enables compound-specific predictions and improves spatial risk assessments for PFAS contamination.

Further, atmospheric deposition also plays a role in spreading PFAS, especially near urban or industrial areas (D'Ambro et al., 2023). These persistent compounds can be transported over long distances via air and precipitation, leading to soil contamination far from their original sources. In addition to atmospheric inputs, runoff from industrial sites and landfills contributes substantially to PFAS accumulation in adjacent agricultural fields (Hepburn et al., 2019). Moreover, irrigation using groundwater presents another critical pathway for PFAS entry into soils, especially in regions where aquifers are affected by industrial or municipal discharges (Johnson, 2022). This route of contamination is particularly concerning for agricultural sustainability, as it may lead to long-term soil and crop exposure. Collectively, these pathways underscore the widespread and multifaceted nature of PFAS contamination, reinforcing the urgency for integrated monitoring and mitigation strategies.

Understanding PFAS behavior in agricultural soils is critical for several reasons. PFAS, or *per-* and polyfluoroalkyl substances, are persistent contaminants that interact with soil components, including organic matter and minerals, influencing their mobility and persistence (Bolan et al., 2021). These interactions can lead to the leaching of PFAS into groundwater, affecting drinking water quality and aquatic ecosystems (Ghisi et al., 2019). Additionally, PFAS can disrupt soil microbial communities, alter nutrient cycling and potentially reduce soil fertility (Sarkar et al., 2021). From an agricultural perspective, the uptake of PFAS by crops raises significant concerns about food safety (Marchuk et al., 2023). Crops grown in contaminated soils can accumulate PFAS in edible tissues, posing health risks to consumers, such as immune system suppression, kidney and testicular cancer, and changes in liver enzymes (EPA, 2020). Moreover, the bioaccumulation of PFAS in livestock feeding on contaminated forage can further amplify risks along the food chain (Death et al., 2021). The importance of studying PFAS in agricultural soils extends beyond immediate health risks, encompassing broader environmental and economic impacts. Contaminated soils can

Table 1
Summarizes the leaching potential of PFAS under different irrigation scenarios and soil types.

Irrigation scenario	Soil type	PFAS leaching (cm)	PFAS Concentration in leachate (ng/L)	Leaching potential	References
Low irrigation (Weekly)	Sandy soil	3	1500	High	EPA, 2021a, 2021b, 2021c, 2021d
Moderate irrigation (Biweekly)	Loam	6	500	Moderate	USDA, 2024a, 2024b, 2024c
High irrigation (Daily)	Clay soil	10	200	Low	European Commission, 2024 a,b
High irrigation (Daily with Mulch)	Loamy Sand	5	800	Moderate	EFSA, 2024

lead to reduced crop yields and quality, affecting the agricultural economy and food security. The persistence of PFAS in the environment means that contamination can have long-term effects, necessitating ongoing monitoring and management efforts. Furthermore, the lack of standardized methods for assessing and managing PFAS contamination creates significant challenges for policymakers and agricultural stakeholders. Developing effective remediation strategies, such as adsorption, bioremediation, and phytoremediation, is crucial to mitigate PFAS bioavailability and environmental risks. These strategies not only help in reducing contamination but also promote sustainable agricultural practices. Addressing the challenges posed by PFAS contamination requires interdisciplinary research, standardized methodologies, and collaborative efforts among scientists, policymakers, and agricultural stakeholders. To address these challenges, the following objectives guide the scope and structure of this review. This review aims to provide a comprehensive analysis of PFAS contamination in agricultural soils, focusing on measurement and modeling approaches (Fig. 1). Specifically, it seeks to explore the chemical and physical properties of PFAS that determine their behavior in soil environments. It reviews the latest analytical techniques used to measure PFAS concentrations in agricultural soils, highlighting their accuracy and limitations. Additionally, it examines modeling approaches for predicting the fate and transport of PFAS in soil systems. The review discusses the ecological and agricultural impacts of PFAS contamination, with an emphasis on soil health and crop productivity. Furthermore, it evaluates current mitigation and remediation strategies, proposing future directions for sustainable soil management. By addressing these objectives, the review intends to bridge existing knowledge gaps and propose actionable strategies for mitigating PFAS risks in agriculture. The scope of this review encompasses a detailed examination of PFAS behavior, impacts, and management within agricultural ecosystems. The review begins by discussing the characteristics of PFAS and their interactions with soil components. It then delves into the ecological impacts of PFAS contamination, emphasizing soil health and agricultural productivity. Measurement techniques and modeling approaches are critically analyzed, providing insights into their application and limitations. Finally, the review evaluates current and emerging mitigation strategies, identifying areas for future research and innovation.

2. Methodology

This review and meta-analysis on PFAS soil dynamics, predictive modeling, and policy integration was conducted with adherence to PRISMA-inspired principles to ensure clarity and rigor, while employing a flexible selection approach to incorporate diverse relevant data. A systematic literature search was conducted to identify peer-reviewed studies, technical reports, and institutional publications relevant to PFAS fate, remediation, policy and soil dynamics related to it. The keywords guiding selection included *Soil, PFAS, Remediation, Policy, Contaminants, Microbiota,* and *Bioaccumulation*. Included studies addressed empirical data, transport and fate modeling, or policy analysis directly related to PFAS in soils. The search encompassed three major bibliographic databases—PubMed, Scopus, and Web of Science—using a combination of controlled vocabulary and keyword strings tailored to each platform. No date restrictions were applied, and the search was finalized in August 2025 (Fig. 2). Additionally, grey literature was retrieved from authoritative websites and organizational repositories, including the U.S. Environmental Protection Agency (EPA), European Food Safety Authority (EFSA), United States Department of Agriculture (USDA), Interstate Technology & Regulatory Council (ITRC), Strategic Environmental Research and Development Program (SERDP), and others. The inclusion criteria for the studies were based on original research or technical findings relevant to the review scope, were published in English, and provided sufficient methodological detail for quality assessment, while the exclusion for the review included duplicates across databases or sources, non-English publications, conference abstracts without full-text availability, and documents lacking relevance to the core research questions. All retrieved records were imported into a reference management system, where duplicates ($n = 12$) were automatically removed. Titles and abstracts of the remaining records ($n = 133$) were screened independently by two reviewers. Full texts were sought for 50 reports and other documents, of which 2 could not be retrieved due to access limitations. A total of 145 references were included in the final synthesis. This comprises 95 peer-reviewed journal articles and 48 technical reports or institutional publications that met all inclusion criteria. Additionally, 2 supplementary records—such as policy briefs or data repositories—were retained due to their high relevance and unique contribution to the review's thematic scope, despite not fitting neatly into the primary categories. These supplementary records were not part of the initial full-text screening pool but were added post hoc during the synthesis phase based on expert recommendation and citation within included studies. Their inclusion ensures completeness and contextual depth, particularly for emerging frameworks or datasets not yet indexed in conventional databases. Data extraction followed PRISMA 2020 guidelines (Haddaway et al., 2022). The flow of information through the phases of identification, screening, eligibility, and inclusion is summarized in the PRISMA flow diagram (Fig. 2). Specific database yields were: PubMed ($n = 210$), Scopus ($n = 230$), and Web of Science ($n = 235$). No records were retrieved from clinical trial registers. The reasons for exclusion during full-text assessment included outdated methodology ($n = 3$), insufficient detail ($n = 2$), and duplicate content ($n = 2$). All included records were categorized into studies and reports, with recent publications (2023–2025) flagged as new contributions to the field.

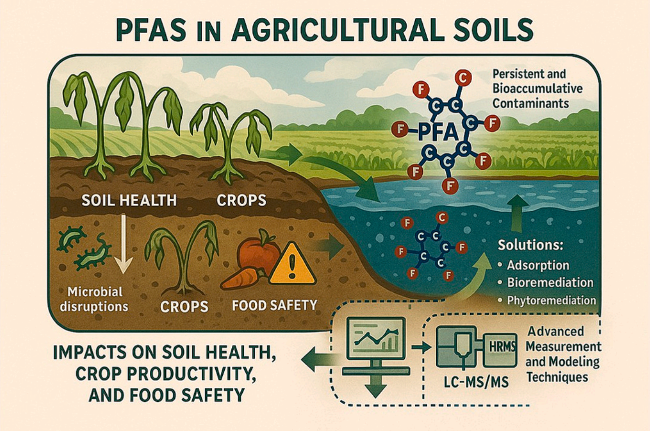

Fig. 1. A conceptual diagram summarizing PFAS transport and transformation pathways in agricultural soils.

3. PFAS in agricultural soil: characteristics and behavior

PFAS are a diverse group of compounds characterized by carbon-fluorine bonds, one of the strongest in organic chemistry (Glüge et al., 2020). This bond imparts high thermal and chemical stability, making PFAS resistant to degradation in natural environments (Diaz and Stewart, 2019). Common PFAS compounds such as perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) exhibit amphiphilic properties due to their hydrophobic fluorinated tail and hydrophilic functional group, influencing their behavior in soil matrices (Christensen et al., 2022; Guelfo and Higgins, 2013). The partitioning behavior of PFAS between solid and liquid phases in soil is primarily determined by their chain length and functional groups (Luft et al., 2022). Long-chain PFAS tends to bind more strongly to organic matter and soil particles due to hydrophobic interactions, while short-chain PFAS are more soluble, making them more mobile in the soil and prone to leaching into groundwater (Bolan et al., 2021). These

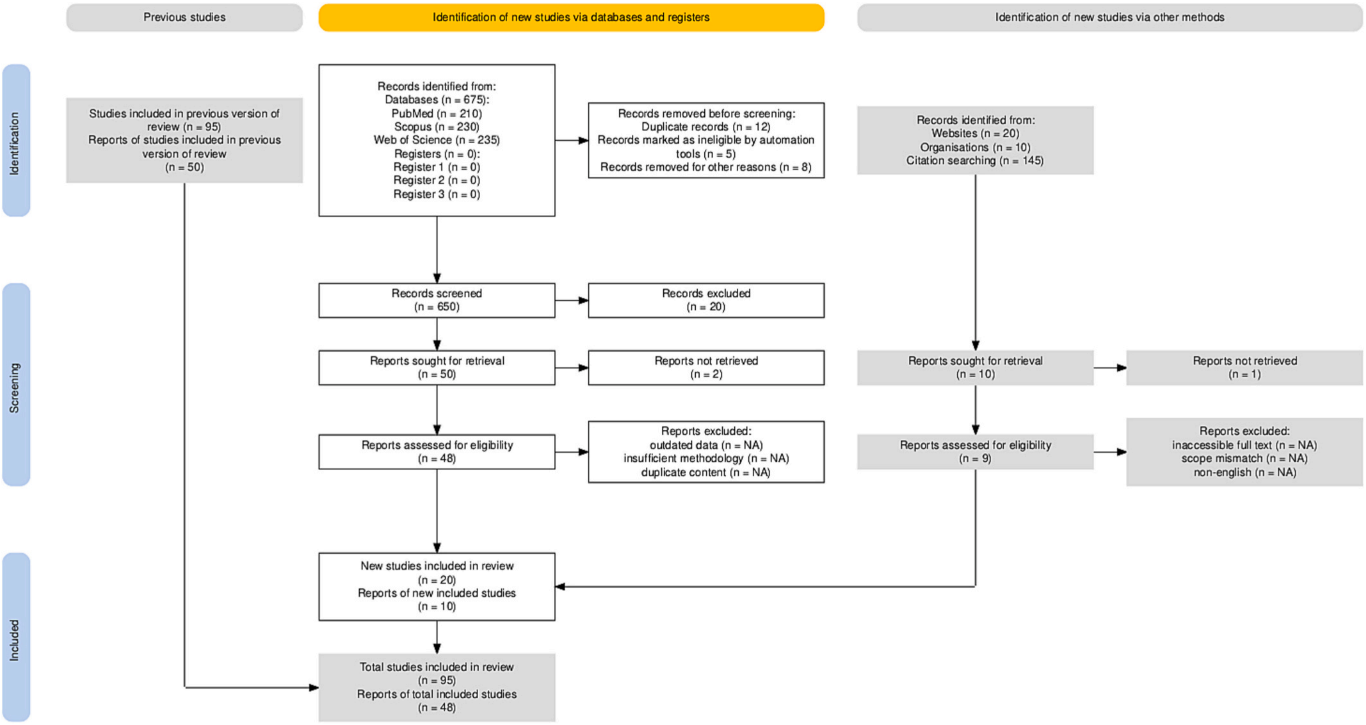

Fig. 2. PRISMA flow diagram summarizing the identification, screening, eligibility, and inclusion of records for the systematic review.

properties make PFAS highly persistent and difficult to remediate once introduced into soil systems. In addition to hydrophobic and electrostatic interactions, PFAS can also form hydrogen bonds and undergo coordination or complexation with soil minerals such as metal oxides and clays (Luft et al., 2022). These interactions further enhance PFAS retention in soil, particularly under varying pH and ionic strength conditions, contributing to their environmental persistence. In addition, PFAS compounds can be taken up by crops, with accumulation patterns influenced by molecular structure, soil properties, and plant physiology (Costello and Lee, 2024). Short-chain PFAS are generally more mobile and tend to accumulate in above-ground tissues such as leaves, while long-chain PFAS are more likely to remain in root zones due to stronger sorption to soil particles (Groffen et al., 2023a). Uptake mechanisms include both passive and active transport and vary across plant species and environmental conditions such as temperature and soil organic content (Groffen et al., 2023b). Mechanistic models incorporate factors like transpiration stream concentration, root uptake rates, and soil–plant partitioning to simulate PFAS transfer, while empirical models use bioaccumulation factors (BAFs) to estimate PFAS concentrations in edible plant tissues (Costello and Lee, 2024). These modeling approaches support exposure assessments and help evaluate food safety risks associated with PFAS-contaminated agricultural systems.

3.1. Interaction with soil components

PFAS interactions with soil are governed by multiple factors, including organic matter content, pH, cation exchange capacity, and the presence of competing anions (Nguyen et al., 2020). Organic matter plays a crucial role in adsorbing PFAS, particularly those with long fluorocarbon chains, through nonpolar interactions (Stebel et al., 2019). In contrast, clay minerals and oxides exhibit limited adsorption capacity for PFAS, although electrostatic interactions with functional groups can occur under specific conditions electrostatic interactions with functional groups can occur (Mukhopadhyay et al., 2021). Additionally, hydrogen bonding and coordination/complexation mechanisms may contribute to PFAS retention on mineral surfaces, particularly in the presence of transition metals or hydroxylated oxides. These interactions can enhance sorption affinity, especially for PFAS compounds with polar functional groups such as carboxylates and sulfonates. Soil pH further modulates these processes: acidic conditions tend to promote adsorption due to protonation of mineral surfaces and PFAS functional groups, whereas alkaline conditions may favor desorption and increased mobility (Vakili et al., 2024). Moreover, salinity and the presence of competing anions—such as sulphate, nitrate, or phosphate—can displace PFAS from binding sites, facilitating their transport through the soil matrix (Abou-Khalil et al., 2022). Understanding these multifaceted interactions is critical for predicting PFAS behavior, including their transport, bioavailability, and persistence in agricultural soils. Table 2 presents representative PFAS compounds detected in agricultural soils, along with their chemical properties and environmental behavior. This data illustrates how molecular characteristics influence PFAS interactions with soil components, including their tendency for adsorption, mobility, and persistence under varying conditions. Also, it illustrates how molecular characteristics—such as chain length, functional group polarity, and acid dissociation constants—influence PFAS interactions with soil components, shaping their adsorption potential, mobility, and long-term environmental fate. The leaching potential of PFAS varies significantly based on irrigation scenarios and soil types. For instance, sandy soil with low irrigation has the highest leaching potential, while clay soil with high irrigation has the lowest. The addition of mulch in loamy sand under high irrigation reduces leaching potential to a moderate level. These findings highlight the importance of soil type and irrigation practices in managing PFAS contamination (EPA, 2021a, 2021b, 2021c, 2021d).

In addition to chemical interactions, PFAS contamination can significantly affect soil microbial communities, with cascading effects on agroecosystem functioning. Exposure to PFAS such as PFOS, PFOA, and PFBS has been shown to alter microbial diversity and abundance, particularly among bacterial and fungal populations (Xu et al., 2023). These compounds can inhibit soil respiration and enzymatic activities such as dehydrogenase and phosphatase, which are essential for organic matter decomposition and nutrient cycling (Fabregat-Palau et al., 2025). At elevated concentrations, PFBS has been found to disrupt nitrogen cycling by suppressing key nitrifying taxa like Nitrososphaerota, while

Table 2
Summary of PFAS compounds detected in agricultural soils (EPA, 2021a, 2021b, 2021c, 2021d).

PFAS compound	Molecular formula	Chemical abstracts service number	Typical concentration range	Source	Environmental behavior
PFOA	$C_8HF_{15}O_2$	335-67-1	0.1–10 μg/kg	Biosolid application, wastewater	Persistent, long-range mobility
PFOS	$C_8HF_{17}O_3S$	1763-23-1	0.5–20 μg/kg	Industrial discharge, runoff	Bio accumulative, hydrophobic
PFHxS	$C_6HF_{13}O_3S$	355-46-4	0.3–5 μg/kg	Industrial runoff	Moderate persistence
PFBA	$C_4HF_7O_2$	375-22-4	0.02–3 μg/kg	Irrigation water	Shorter persistence, leachable
PFPeA	$C_5HF_9O_2$	2706-90-3	0.1–5 μg/kg	Wastewater effluent	Highly mobile in soils

simultaneously triggering compensatory increases in urease and phosphatase activity (Yan et al., 2025). Such disruptions can impair soil health, reduce fertility, and compromise ecosystem resilience. Beyond microbial impacts, PFAS contamination also influences plant uptake and accumulation dynamics. Different crops exhibit varying capacities to absorb and translocate PFAS, with leafy vegetables and root crops often showing higher accumulation levels due to their extensive contact with contaminated soils and water. The physicochemical properties of individual PFAS compounds—such as chain length, functional groups, and hydrophobicity—play a critical role in determining their bioavailability and uptake potential. Mechanistic models based on soil–plant partitioning coefficients and transpiration stream concentration factors (TSCF) have been developed to predict PFAS accumulation in crops under controlled conditions. Additionally, empirical models incorporating crop type, soil characteristics, and irrigation sources are increasingly used to estimate PFAS concentrations in edible plant tissues across diverse field scenarios. Together, these findings underscore the need for integrated assessments that consider both microbial and plant-level responses to PFAS contamination. Such approaches are essential for developing predictive frameworks and mitigation strategies aimed at safeguarding soil health, crop safety, and food system sustainability in PFAS-impacted agroecosystems.

4. Impacts of PFAS on soil health and agriculture

PFAS contamination can disrupt these processes by altering microbial composition and activity. Studies have shown that long-chain PFAS, due to its hydrophobic nature, can accumulate in microbial cell membranes, affecting cellular integrity and metabolic functions (Nguyen et al., 2020). Changes in microbial diversity and abundance have been observed in PFAS-contaminated soils, with certain species exhibiting tolerance or resistance. These shifts can lead to imbalances in ecosystem functions, such as reduced decomposition rates or impaired nutrient cycling. The long-term ecological consequences of such disruptions remain poorly understood and warrant further investigation (Brase et al., 2021).

PFAS contamination can indirectly affect soil fertility by altering microbial-mediated processes (Shahsavari et al., 2021). For instance, the inhibition of nitrogen-fixing bacteria can reduce the availability of essential nutrients for plant growth (Senevirathna et al., 2022). Additionally, PFAS interactions with soil organic matter can influence aggregate stability and water retention, further affecting soil structure and productivity (Hubert et al., 2023). Soil enzyme activity, a key indicator of soil health, is also impacted by PFAS exposure. Enzymes involved in organic matter decomposition and nutrient cycling, such as dehydrogenase and phosphatase, exhibit reduced activity in PFAS-contaminated soils (Sanchez-Hernandez et al., 2024). These changes can have cascading effects on soil fertility and agricultural productivity.

One of the most concerning aspects of PFAS contamination is their uptake by crops. PFAS can enter plant systems through root absorption (Ramakrishnan et al., 2021), with their accumulation depending on soil properties, PFAS concentrations, and crop type (Lesmeister et al., 2021). Short-chain PFAS are more likely to translocate to edible plant tissues, increasing the risk of human exposure (Maddela et al., 2022). The bioaccumulation of PFAS in livestock is another significant concern (Ramakrishnan et al., 2021). Animals grazing on contaminated forage or drinking PFAS-laden water can accumulate these compounds in their tissues, particularly in organs such as the liver and kidneys (Witt et al., 2024). This bioaccumulation has implications for food safety, necessitating stringent monitoring of PFAS levels in agricultural products (Brunn et al., 2023).

5. Measurement techniques for pfas in agricultural soils

5.1. *Traditional analytical techniques*

5.1.1. *Liquid chromatography-mass spectrometry (LC-MS/MS)*

Liquid chromatography coupled with tandem mass spectrometry (LC-MS/MS) is a key method for detecting and quantifying PFAS in soils (Dodds et al., 2020). LC separates PFAS compounds, while MS/MS identifies and quantifies them by measuring their mass-to-charge ratios. LC-MS/MS offers high sensitivity and specificity, detecting low PFAS concentrations in complex soil matrices (Fig. 3). It can analyze multiple PFAS compounds simultaneously, making it ideal for monitoring contaminated sites. However, LC-MS/MS is costly, requires skilled technicians, and involves labor-intensive sample preparation. Soil matrices can introduce interferences, and the technique requires large solvent volumes, posing environmental concerns (CSWRCB, 2024). A California study used LC-MS/MS to analyze PFAS in soils irrigated with reclaimed water. Soil samples from 0 to 15 cm and 15–30 cm depths were examined for 14 PFAS compounds, including PFOA and PFOS. Concentrations ranged from 0.1 to 35 μg/kg in topsoil and 0.05 to 10 μg/kg in subsoil, with PFOA being most prevalent. The study demonstrated LC-MS/MS's capability to achieve detection limits as low as 0.05 μg/kg (CSWRCB, 2024; Felizeter et al., 2021; Willey et al., 2024).

5.1.2. *Gas chromatography-mass spectrometry (GC–MS)*

Gas chromatography-mass spectrometry (GC–MS) is another commonly used method for PFAS analysis, particularly effective for analyzing volatile or semi-volatile PFAS compounds (Androulakakis et al., 2022), such as PFOS and PFOA, in soil samples (Fig. 3). GC–MS is highly sensitive and can detect PFAS compounds at very low concentrations (Brusseau et al., 2020). It is a well-established method with a large body of research supporting its application in environmental analysis. However, GC–MS is less suitable for analyzing long-chain PFAS compounds that are non-volatile and have high molecular weights (Chiang, 2024). Complementary techniques such as solid-phase microextraction (SPME) and passive sampling have enhanced PFAS detection in environmental matrices (Shen et al., 2024). SPME enables solvent-free pre-concentration and is compatible with GC–MS, while passive samplers like POCIS allow time-integrated monitoring of PFAS in soil and water, improving detection of trace-level contaminants (Li et al., 2016). Additionally, Solid-Phase Extraction (SPE) is commonly used prior to GC–MS to concentrate PFAS analytes and remove matrix impurities, improving detection accuracy and reducing background interference. GC–MS was employed to analyze volatile PFAS precursors in soils near industrial facilities. Soil samples contained PFAS precursor concentrations of up to 20 μg/kg, primarily shorter-chain compounds

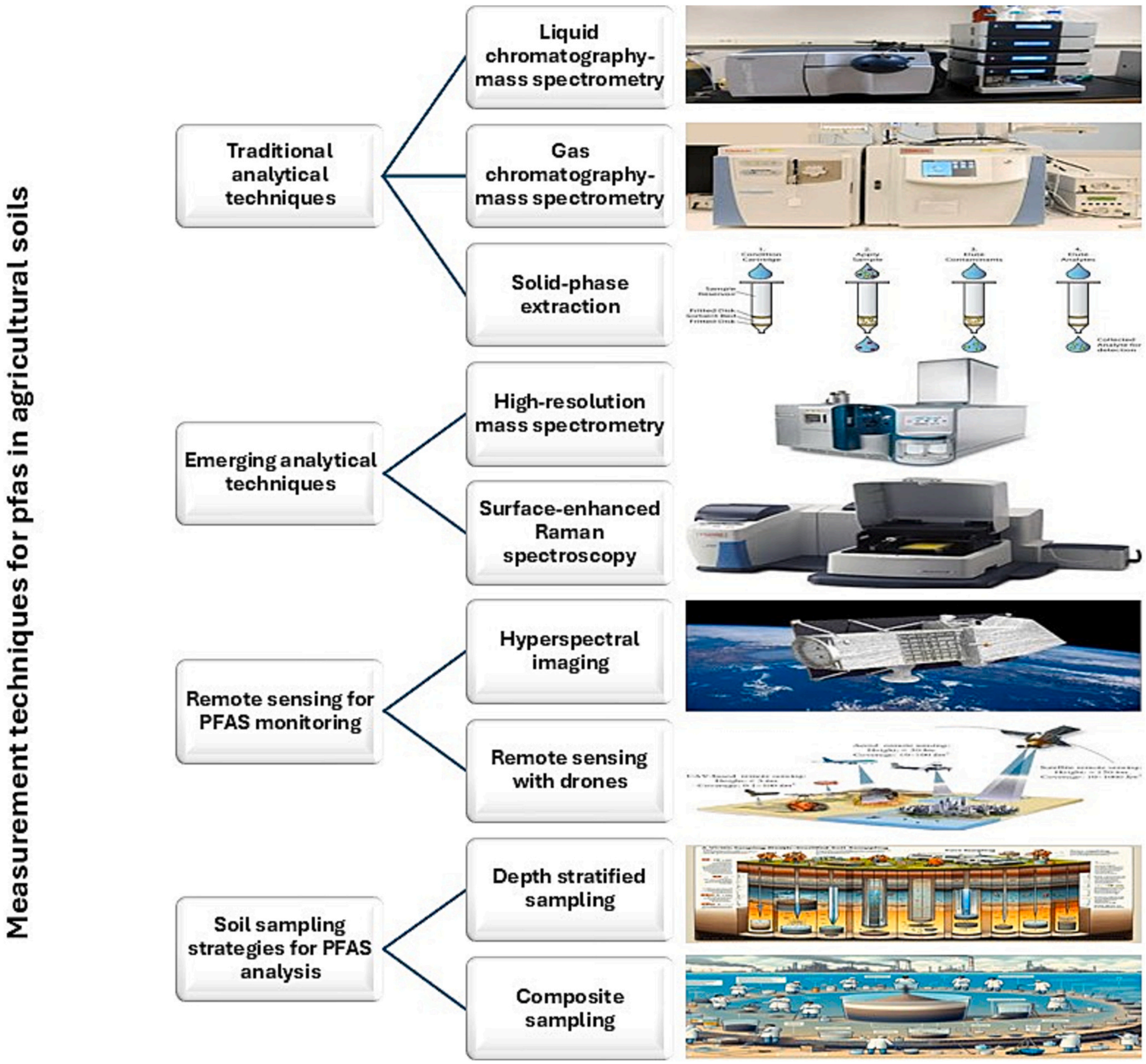

Fig. 3. Different measurements technique of PFAS.

like 6:2 fluorotelomer alcohols. Over 60 % of detected precursors transformed into persistent PFAS within six months under simulated environmental conditions. This demonstrated GC–MS's effectiveness in characterizing volatile PFAS with LODs of 0.1 μg/kg, although it required labor-intensive sample preparation (Brusseau et al., 2020; Chiang, 2024).

5.1.3. Solid-phase extraction (SPE)

SPE is often used as a sample preparation technique for PFAS analysis in soil (Lockwood et al., 2019). This method involves the use of a solid adsorbent material, such as silica or activated carbon, to concentrate PFAS compounds from soil extracts (Conquer Scientific, 2024). The concentrated PFAS are then analyzed using techniques like LC-MS/MS or GC–MS. SPE is effective for concentrating PFAS compounds from soil extracts, which is particularly useful for low-concentration samples. It is also a relatively simple and cost-effective sample preparation technique (Conquer Scientific, 2024). However, SPE can sometimes result in incomplete extraction of PFAS from the soil matrix, particularly for strongly bound PFAS compounds (Pan et al., 2017). The method also requires careful selection of the adsorbent material to ensure maximum recovery of PFAS compounds. A study combined SPE with LC-MS/MS to detect PFAS in soils irrigated with wastewater. The process achieved recovery rates between 85 % and 95 %, even for highly sorbed PFAS like PFHxS. Concentrations varied from 0.05 to 50 μg/kg, with a median of 5 μg/kg for PFOS. SPE significantly improved the analytical sensitivity, reducing matrix effects by 70 % compared to direct injection methods (Houtz et al., 2013; Pan et al., 2017). In addition to SPE, SPME has emerged as a solvent-free alternative for PFAS sampling. SPME uses a coated fiber to extract analytes directly from soil slurries or headspace, offering minimal sample handling and compatibility with GC–MS and LC-MS platforms. Though traditionally applied to volatile and semi-volatile compounds, recent advances in fiber coatings have improved PFAS selectivity and sensitivity, especially for short-chain variants. Passive sampling techniques, such as the use of polar organic chemical integrative samplers (POCIS), are also gaining traction for long-term monitoring of PFAS in soil pore water. These samplers accumulate

PFAS over time, providing time-weighted average concentrations and reducing the need for frequent sampling. Passive samplers are particularly useful in field settings where continuous monitoring is required, and they help capture episodic contamination events that may be missed by grab sampling. Together, these complementary approaches—SPE, SPME, and passive sampling—enhance the analytical toolkit for PFAS detection in soils, enabling more accurate quantification across diverse environmental matrices and concentration ranges.

5.2. Emerging analytical techniques

5.2.1. High-resolution mass spectrometry (HRMS)

High-resolution mass spectrometry (HRMS) is an advanced technique that delivers highly accurate and detailed measurements of PFAS in soils (Fig. 3). Unlike traditional mass spectrometry, HRMS offers superior mass accuracy and resolution, enhancing the detection of complex PFAS mixtures and structural isomers (Röhler et al., 2021). HRMS provides exceptional sensitivity and precision, even for trace PFAS concentrations (Bugsel et al., 2021). It can analyze a broad range of PFAS compounds, including isomers and previously unidentified compounds, making it a powerful tool for comprehensive PFAS monitoring (Strynar et al., 2023). Researchers in Germany used HRMS to profile 32 PFAS compounds in agricultural soils near a fluoropolymer manufacturing facility. PFAS concentrations ranged from 0.1 to 120 μg/kg, with novel compounds comprising 15 % of the total. HRMS identified fluorotelomer sulfonates and perfluoroether carboxylic acids, previously unreported in the region. Its high resolving power provided isotopic ratio confirmation, ensuring precise source attribution (Bugsel et al., 2021; Röhler et al., 2021).

5.2.2. Surface-enhanced Raman spectroscopy (SERS)

Surface-enhanced Raman spectroscopy (SERS) is an emerging technique that uses Raman scattering to detect molecular vibrations of PFAS compounds (Fig. 3), with enhanced sensitivity provided by nanoparticles or roughened surfaces that amplify the signal (Kukralova et al., 2024). SERS is a rapid, non-destructive method that can detect PFAS at very low concentrations in complex matrices like soil (Conquer Scientific, 2024). The technique is portable, allowing for field-based measurements without the need for sample transport to a laboratory (Restaino and White, 2019). However, SERS requires the preparation of nanomaterials or rough surfaces, and the technique may not be as reliable for all PFAS compounds, particularly those with low Raman scattering intensities (Bhavya et al., 2023). The SERS method also requires optimization for specific PFAS species and might not be as widely applicable across different soil types (Rothstein et al., 2024). Researchers employed SERS for on-site PFAS detection in soils contaminated by industrial effluents (SERDP, 2024a). Using silver nanoparticle substrates, SERS achieved LODs of 0.5 μg/kg for PFOA and PFOS. Soil samples from the top 10 cm exhibited contamination levels between 1 and 25 μg/kg. While SERS allowed rapid screening within 30 min, spectral overlap among PFAS limited its applicability to simple matrices (Rothstein et al., 2024; Yadav and Srivastava, 2024).

5.3. Remote sensing for PFAS monitoring with drones

Hyperspectral imaging captures images at hundreds of wavelengths across the electromagnetic spectrum (Fig. 3). By analyzing spectral signatures, researchers can detect specific contaminants, including PFAS, based on unique absorption patterns (Satelytics, 2020). This technology can cover large areas rapidly and provide high-resolution data on PFAS distribution in agricultural fields, using drones, satellites, or aircraft (Liu et al., 2024). However, PFAS compounds lack strong spectral features in many parts of the spectrum, making direct detection challenging. Researchers are exploring methods to correlate spectral data with soil contamination levels using statistical models or machine learning (Satelytics, 2020). McGuire et al. (2014) used hyperspectral imaging to visualize relative concentration trends between shallow and deep soil samples. Data showed that shallow soil samples had total PFAA concentrations exceeding 5000 μg/kg, while deeper samples at the water table had significantly lower concentrations, indicating limited vertical migration of PFAAs due to high clay content and organic matter in the vadose zone (McGuire et al., 2014).

Unmanned aerial vehicles (UAVs), or drones, equipped with various remote sensing technologies, are becoming increasingly popular for environmental monitoring (Fig. 3). Drones can be used to gather data on soil conditions, crop health, and even detect environmental stressors that may be linked to PFAS contamination, such as changes in plant growth or water availability (Srivastav et al., 2024). Drones can access hard-to-reach areas and provide high-resolution imagery in real-time, which is valuable for monitoring large-scale contamination or tracking changes over time. UAVs can also be equipped with multiple sensors, such as thermal infrared or multispectral cameras, to detect subtle environmental changes associated with PFAS contamination (Hansen et al., 2023). However, drones can be limited by flight duration, payload capacity, and regulatory restrictions in certain regions (Otto et al., 2018). While they can provide useful data for assessing general trends, they may not offer the level of specificity required for direct measurement of PFAS concentrations in soil (Hansen et al., 2023). A pilot study integrated drone-based hyperspectral imaging with LC-MS/MS ground validation to monitor PFAS in agricultural fields (Farmonaut, 2024). The remote sensing data detected contamination hotspots with a 90 % accuracy rate compared to laboratory measurements. Concentrations in affected soils ranged from 0.2 to 40 μg/kg. This method reduced field sampling costs by 30 % and provided spatial resolution as fine as 1 m, making it a cost-effective solution for large-scale monitoring (Guo et al., 2023).

5.4. Soil sampling strategies for PFAS analysis

To ensure accurate PFAS measurements in agricultural soils, a carefully selected sampling strategy is essential. Depth-stratified sampling, which collects soil from multiple depths, is valuable for detecting potential vertical migration (EPA, 2023). Surface soil sampling (0–10 cm) is cost-effective for initial surveys but may miss deeper contamination, while core sampling (0–100 cm) provides comprehensive vertical profiles but is more labor-intensive and requires specialized equipment. Grab sampling can be useful for targeted locations but may not capture spatial variability (FRTR, 2023). Composite sampling, which combines multiple samples from different points within an area, can reduce variability and provide an average PFAS concentration over a larger zone, but it may also dilute localized peaks and mask contamination hotspots (ITRC, 2023a, 2023b).

Studies (Brusseau et al., 2020; Sanchez-Hernandez et al., 2024) comparing three approaches reported that in that specific case, stratified random sampling detected PFAS concentrations ranging from 0.1 to 60 μg/kg with lower variance than grid-based or composite sampling, reducing sampling error by about 25 %. While these findings suggest potential advantages for capturing variability related to soil texture and land use, they are based on a single dataset from a single site and should be interpreted with caution. Broader, multi-site studies would be needed to determine whether these results are consistent under different soil types, land uses, and contamination patterns. Recent investigations (Pulster et al., 2024; Darkwah, 2023) have begun to address this gap by applying stratified and depth-integrated sampling across diverse landscapes. Pulster et al. (2024) emphasized the importance of tailoring sampling protocols to hydrological and land-use contexts, noting that PFAS retention and mobility are strongly influenced by site-specific factors such as soil permeability, organic carbon content, and proximity to known point sources. Darkwah (2023) demonstrated the utility of GIS-integrated soil core sampling for delineating PFAS hotspots in agricultural zones, using geostatistical interpolation techniques (e.g., kriging) to visualize subsurface contamination gradients and identify zones of elevated risk. These multi-site approaches reinforce the potential of stratified designs to improve detection accuracy and spatial resolution, especially when combined with geospatial modeling and risk-based prioritization frameworks. Moreover, Brusseau et al. (2020) compiled over 30,000 soil samples from 2500 sites globally, revealing that PFAS concentrations in soils are often orders-of-magnitude higher than in groundwater, particularly in the vadose zone, underscoring the need for depth-resolved sampling and long-term monitoring strategies. Collectively, these studies support the refinement of PFAS sampling protocols to accommodate environmental heterogeneity and enhance the reliability of contamination assessments across varied land-use and soil typologies.

6. Modeling of PFAS

PFAS modeling simulates the distribution, transport, and degradation of these contaminants in soil, water, and air. These models predict PFAS movement over time, assess groundwater contamination risk, and evaluate remediation strategies (ITRC, 2023a, 2023b). PFAS modeling involves transport modeling, which simulates PFAS movement through soil and groundwater, and fate modeling (Fig. 4), which predicts degradation, persistence, and bioaccumulation in different environments (EPA, 2023). These models consider physical, chemical, and biological processes, including adsorption, desorption, volatilization, leaching, and transformation (Armitage, 2009). Due to the variety of PFAS compounds, models must account for diverse interactions with the soil environment (ITRC, 2023a, 2023b).

6.1. Transport models for PFAS in soil

Advection-dispersion models (ADMs) are commonly used to simulate PFAS transport in soils and groundwater (Table 3). These models treat PFAS as solutes moving with water flow, accounting for dispersion due to soil heterogeneity (Guo et al., 2020). ADMs are applicable in both saturated and unsaturated soils and can incorporate site-specific data like soil properties and hydraulic conductivity to predict PFAS movement over time. However, ADMs depend heavily on accurate input parameters, such as soil porosity, water velocity, and PFAS sorption coefficients, leading to uncertainties due to soil composition variability (Farid and Iradukunda, 2023). HYDRUS and MODFLOW with MT3DMS models (Table 3) simulate PFAS movement through soil and groundwater. Anderson et al. (2016) used HYDRUS to predict PFAS transport in sandy soils, demonstrating its effectiveness under different groundwater conditions. Silva et al. (2022) applied HYDRUS to loamy soils, showing its utility in understanding PFAS behavior. Raschke et al. (2022) and Pietrzak (2021) used MODFLOW with MT3DMS to model PFAS dispersion in clay soils, highlighting its effectiveness in complex hydrogeological settings.

Multicomponent transport models consider interactions between multiple chemicals in soil and water (Table 3), accounting for PFAS coexisting with other contaminants like nutrients, heavy metals, and organic pollutants (Kim et al., 2019). These models simulate complex interactions, providing a realistic representation of contamination behavior but require extensive input data on concentrations, properties, and interactions of various chemicals (Horst et al., 2020). PHT3D and COMSOL Multiphysics models are used to simulate these interactions (Monjezi et al., 2017). Horst et al. (2020) used PHT3D to simulate PFAS transport with other contaminants, offering insights into multi-contaminant scenarios. Newell et al. (2021a) applied PHT3D to agricultural soils, demonstrating its utility in complex environments. Sookhak Lari et al. (2024) and Kim et al. (2019) used COMSOL Multiphysics to model PFAS interactions in loamy sand, showing its effectiveness in various soil types.

Soil-water partitioning models focus on how PFAS compounds partition between soil particles and soil pore water (Table 3). These models use sorption coefficients to describe PFAS adsorption to soil organic matter, clay minerals, and other components, helping predict PFAS leaching and potential groundwater contamination (Nguyen et al., 2020). However, determining sorption coefficients is challenging due to soil variability and complex PFAS interactions (ITRC, 2020). Thompson et al. (2024) used equilibrium partitioning to study PFAS retention in sandy soils, Campos-Pereira et al. (2022) and Mikhael et al. (2024) used Freundlich sorption models to understand PFAS mobility in clay soils, providing insights into PFAS retention and mobility. Brusseau and Guo (2022) developed a comprehensive distribution model incorporating air-water interfacial adsorption, demonstrating that PFAS retention in the vadose zone is significantly influenced by soil texture, moisture content, and compound-specific properties such as chain length and functional groups. Fabregat-Palau et al. (2025) introduced PFA-SorptionML, a machine learning tool trained on over 1200 Kd entries, which integrates soil pH, organic carbon content, and PFAS molecular descriptors to predict sorption behavior across diverse soil types. These advancements highlight the growing emphasis on data-driven and mechanistic approaches to improve sorption coefficient estimation and

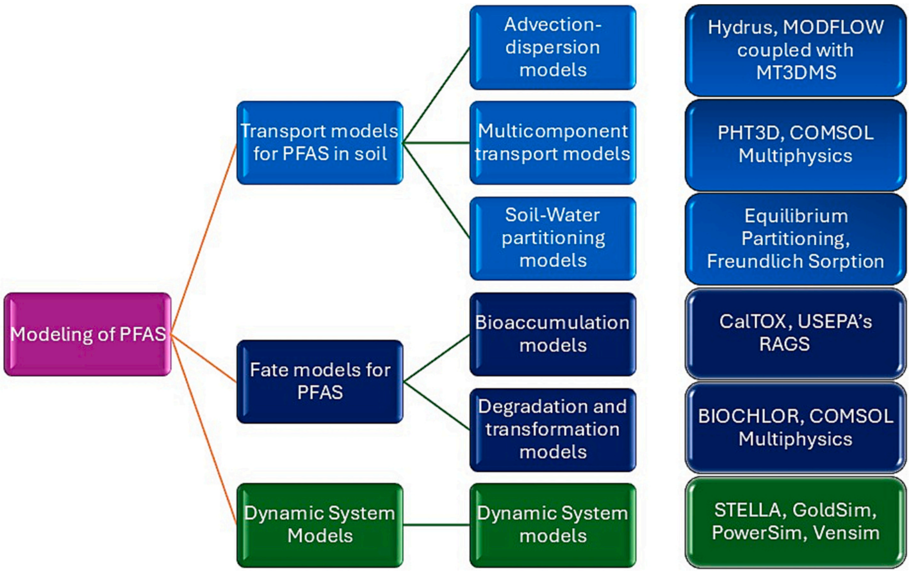

Fig. 4. Different types of modeling in PFAS.

Table 3
Modeling tool for PFAS simulation.

Category	Model type	Model examples	Description	Findings
Transport models	Advection-dispersion models	HYDRUS (Anderson et al., 2016; Silva et al., 2022), MODFLOW with MT3DMS (Raschke et al., 2022; Pietrzak, 2021)	Simulate the movement of PFAS through soil and groundwater.	Effective in predicting PFAS transport in various soil types and groundwater conditions.
	Multicomponent transport models	PHT3D (Appelo and Rolle, 2010; Newell et al., 2021a, 2021b), COMSOL Multiphysics (Sookhak Lari et al., 2024; Kim et al., 2019)	Consider interactions between multiple chemicals in the soil and water system.	Useful for complex scenarios involving multiple contaminants.
	Soil-water partitioning models	Equilibrium Partitioning (Thompson et al., 2024), Freundlich Sorption (Campos-Pereira et al., 2022; Mikhael et al., 2024)	Describe how PFAS compounds partition between soil particles and soil pore water.	Provide insights into PFAS retention and mobility in soils.
	PRZM (pesticide root zone model)	PRZM (Liao et al., 2024; NCASI, 2020, 2021)	Simulates the transport of pesticides and other organic chemicals in the crop root and unsaturated soil zones.	Effective for assessing PFAS leaching in agricultural settings.
	MACRO	MACRO (Gassmann et al., 2021; Weidemann et al., 2022)	Simulates water flow and solute transport in macroporous soils.	Highlights the impact of soil structure on PFAS transport.
Fate models	Bioaccumulation models	CalTOX (Ashraf et al., 2024; Fjeld et al., 2005)	Simulate the uptake and accumulation of PFAS in plants, animals, and soil microorganisms.	Show the potential for PFAS bioaccumulation in various organisms.
	Degradation and transformation models	BIOCHLOR (Newell et al., 2021a, 2021b), COMSOL Multiphysics (Sookhak Lari et al., 2024; Bali et al., 2022)	Simulate the breakdown of PFAS compounds in soil.	Provide insights into PFAS degradation pathways and rates.

reduce uncertainty in PFAS fate modeling.

The Pesticide Root Zone Model (PRZM) simulates the transport of pesticides and other organic chemicals in the crop root and unsaturated soil zones (Table 3). This model is particularly useful for assessing the leaching potential of PFAS in agricultural settings. Liao et al. (2024) used PRZM to evaluate PFAS leaching, demonstrating its effectiveness in predicting PFAS behavior in crop root zones. Their study highlighted the model's ability to simulate PFAS movement through different soil layers, providing valuable insights into potential contamination pathways. Additionally, National Council for Air and Stream Improvement (NCASI, 2020, 2021) applied PRZM to various soil types, showcasing its utility in understanding PFAS transport in diverse agricultural soils. This application emphasized the model's adaptability to different soil properties and conditions, making it a robust tool for environmental risk assessments. Stone Environmental (2021) and NCASI (2021) published a detailed guidance document outlining PRZM implementation for screening-level PFAS assessments, including step-by-step simulations for biosolid-amended soils and comparisons with field data4. The EPA's PRZM3 model, which integrates hydrologic and chemical transport components, has also been revised to incorporate PFAS-specific retention mechanisms such as air-water interfacial adsorption, improving its accuracy for long-chain PFAS compounds (Brusseau and Guo, 2023). These developments underscore PRZM's evolving role in PFAS modeling and its relevance for regulatory decision-making and site-specific risk evaluations.

The MACRO model simulates water flow and solute transport in macroporous soils (Table 3). Gassmann et al. (2021) used MACRO to study PFAS transport in sandy soils, demonstrating the model's effectiveness in predicting PFAS movement in such environments. Weidemann et al. (2022) applied the MACRO model to loamy soils, highlighting the significant impact of soil structure on PFAS transport. These studies underscore the importance of understanding soil properties for effective PFAS remediation. More recently, Weidemann and Gassmann (2024) extended MACRO simulations to include transformation dynamics of PFAS precursors such as 6:2 and 8:2 diPAPs, using lysimeter and column data to evaluate leaching and plant uptake under near-natural conditions. Their work emphasized the role of temperature and soil moisture in precursor degradation and subsequent PFAS mobility. Silva et al. (2020) highlighted the influence of air-water interfacial adsorption in macroporous systems, showing that PFAS retention is significantly enhanced in unsaturated zones due to interfacial partitioning—an effect that MACRO can incorporate through modified retention parameters. Additionally, Wallis et al. (2022) used MACRO-based modeling to identify vadose zone controls on PFAS mobility under semi-arid conditions, demonstrating how climate and preferential flow pathways alter leaching risks. These findings collectively support the use of MACRO as a robust tool for simulating PFAS fate in structured soils, especially when calibrated with site-specific hydraulic and chemical parameters. The model's adaptability to different soil textures, climate regimes, and compound-specific behaviors makes it valuable for risk assessment and remediation planning across diverse agro-environmental settings.

6.2. *Fate models for PFAS in soil*

Bioaccumulation models simulate the uptake and accumulation of PFAS in plants, animals, and soil microorganisms (Table 3). These models help assess the risks associated with PFAS entering the food chain through crop uptake or livestock grazing on contaminated soil (Sun et al., 2022). They are essential for understanding the potential transfer of PFAS from soil to plants and animals, providing key data for risk assessment. However, the complexity of PFAS bioaccumulation is influenced by various factors, including plant species, soil types, climate, and the specific PFAS compound (Lewis et al., 2022). Models must account for the unique bioavailability of different PFAS compounds (Nguyen et al., 2020). Ashraf et al. (2024) used CalTOX to show the potential for PFAS bioaccumulation in various organisms, providing insights into PFAS behavior in the food chain. Fjeld et al. (2005) applied CalTOX to agricultural soils, demonstrating its utility in understanding PFAS bioaccumulation in different environmental settings. Bioaccumulation models like CalTOX use multimedia fate and transport algorithms to simulate PFAS movement from soil to biota. These models incorporate parameters such as soil concentration, bioconcentration factors (BCFs), translocation stem concentration factors (TSCFs), and uptake rates to estimate PFAS accumulation in plant tissues and animal organs. CalTOX calculates steady-state concentrations in various compartments, including soil, water, air, and biota, enabling risk assessments for food chain exposure. The model also accounts for compound-specific properties like chain length and functional groups, which influence bioavailability and uptake efficiency (Ashraf et al., 2024; Fjeld et al., 2005). Recent studies have emphasized the importance of protein-binding affinity and membrane-water partition coefficients in predicting PFAS distribution in biota, particularly for long-chain compounds such as PFOS and PFOA that preferentially accumulate in liver and kidney tissues (Kelly et al., 2024). Mechanistic food web models developed by Sunderland and Gobas have further refined predictions by incorporating species-specific metabolic rates, trophic transfer efficiencies, and renal clearance parameters (Kelly et al., 2024). Additionally, molecular dynamics simulations have demonstrated that functional head groups (e.g., sulfonates vs. carboxylates) significantly influence PFAS degradation and uptake behavior, with sulfonic acids exhibiting higher bioaccumulation potential due to stronger proteinophilic interactions (Bezerra de Souza et al., 2025). The Interstate Technology and Regulatory Council (ITRC) (2020) guidance also highlights that short-chain PFAS, while less bio accumulative, pose greater mobility risks and may still contribute to diffuse exposure through plant uptake and groundwater transport. Collectively, these models and empirical studies provide a robust framework for evaluating PFAS exposure risks across terrestrial and aquatic food webs, and support the refinement of regulatory thresholds based on compound-specific toxicokinetics and ecological vulnerability.

Degradation models simulate the breakdown of PFAS compounds in soil through abiotic processes (e.g., photolysis, hydrolysis) and biotic processes (e.g., microbial degradation) (Table 3). Although PFAS are generally resistant to degradation, certain conditions, such as UV light or microbial activity, can lead to partial breakdown. These models help understand PFAS persistence and potential degradation into less toxic byproducts (Newell et al., 2021a, 2021b). However, due to the high resistance of many PFAS compounds, reliable degradation rates and mechanisms are hard to incorporate, limiting model accuracy (Bali et al., 2022; Sookhak Lari et al., 2024). Newell et al. (2021a, 2021b) used BIOCHLOR to study PFAS degradation in sandy soils, while Sookhak Lari et al. (2024) and Bali et al. (2022) applied COMSOL Multiphysics to understand PFAS transformation in loamy soils. These studies highlight the importance of understanding PFAS behavior in different soil types (Newell et al., 2021a, 2021b; Sookhak Lari et al., 2024; Bali et al., 2022).

Despite advances in PFAS modeling, several challenges remain. The complexity of PFAS behavior in soil and groundwater, combined with limited understanding of their degradation mechanisms, makes it difficult to predict their long-term fate accurately (Raschke et al., 2022). Additionally, the diverse chemical structures of PFAS compounds require customized models for different species, complicating the modeling process (Redmon et al., 2019). However, advancements in computational power, the development of more sophisticated models, and the increasing availability of high-quality environmental data will enhance the accuracy and reliability of PFAS models (Raschke et al., 2022). Future research should focus on improving the representation of PFAS degradation, refining transport models to incorporate soil heterogeneity, and enhancing the ability to simulate large-scale PFAS contamination scenarios (Raschke et al., 2022; Redmon et al., 2019). Risk assessment frameworks are crucial for protecting human health and the environment from PFAS (*Per-* and Polyfluoroalkyl Substances). These frameworks provide standardized methods for evaluating exposure, toxicity, and risk, aiding in site remediation and management decisions. USEPA's RAGS (Risk Assessment Guidance for Superfund) offers a comprehensive framework for assessing risks at hazardous waste sites, ensuring consistent and scientifically sound assessments (Jha et al., 2021). Similarly, the European Chemicals Agency (ECHA) provides guidance on exposure assessment and risk characterization under the REACH regulation, focusing on persistent, bio accumulative, and toxic substances (Rudin et al., 2023). The CARACAS initiative, funded by the European Commission, reviews risk assessment practices across 16 European countries, offering scientific and technical guidance for contaminated sites (Swartjes et al., 2008). Austria's ÖNORM S 2088-2 standard outlines criteria for soil contamination and its effects on humans, plants, and animals, ensuring site-specific risk assessments (Ferguson, 1999). Additionally, the European Commission's Joint Research Centre (JRC) provides guidance on Natech risk management, addressing natural hazard-triggered technological disasters (Girgin et al., 2019). These frameworks help simulate and measure PFAS by providing robust methodologies for assessing their environmental fate and transport, facilitating the development of models that predict PFAS behavior in various media, and aiding in identifying contamination sources, pathways, and impacts. Using these standardized approaches ensures comprehensive, transparent, and scientifically based evaluations.

7. Mitigation and remediation strategies for PFAS

The use of soil amendments to immobilize PFAS has gained traction as a practical remediation strategy. Fig. 5 shows a comparative chart of remediation techniques, highlighting their effectiveness, advantages, and limitations. Amendments such as activated carbon, biochar, and clays like montmorillonite effectively adsorb PFAS, reducing their bioavailability and mobility. Table 4 shows the summary of remediation technique for PFAS in soil. A study in the United States demonstrated that applying 5 % biochar to contaminated soils decreased PFOS leaching by over 80 % in lysimeter experiments (Holly et al., 2024). Similarly, granular activated carbon (GAC) has been shown to effectively adsorb long-chain PFAS, although its performance diminishes for shorter-chain variants due to their higher mobility and lower hydrophobicity (McNamara et al., 2018). While such physical immobilization strategies are widely used in field-scale applications, they primarily serve as containment measures and do not eliminate PFAS from the environment. To address this limitation, microbial degradation is gaining attention as a complementary and potentially transformative approach in PFAS remediation. Recent studies have highlighted the role of *Acidimicrobium* sp. strain A6, an iron-reducing bacterium, in catalysing the reductive defluorination of highly persistent PFAS compounds such as PFOA and PFOS under anaerobic conditions (Jaffé et al., 2024). This process involves the cleavage of carbon–fluorine bonds, which are among the strongest in organic chemistry, making PFAS notoriously resistant to degradation. The ability of strain A6 to initiate defluorination under environmentally relevant conditions—specifically in iron-rich, anoxic subsurface environments—offers a promising biological pathway for long-term PFAS attenuation. However, the kinetics of degradation, the range of PFAS congeners affected, and the stability of intermediate products remain active areas of investigation. In parallel, the application of soil amendments such as biochar, clay minerals, and organic composts continues to be explored as a cost-effective and environmentally sustainable strategy for PFAS immobilization. These amendments can alter soil physicochemical properties, enhance sorption capacity, and reduce PFAS leaching potential. Nevertheless, their effectiveness is highly site-specific, depending on factors such as soil texture, organic matter content, pH, and the concentration and speciation of PFAS contaminants (Sleep and Juhasz, 2021; Conquer Scientific, 2024). Therefore, integrated approaches that combine physical, chemical, and biological strategies—tailored to local geochemical and hydrological conditions—are increasingly viewed as essential for achieving durable and scalable PFAS remediation outcomes.

Electrochemical oxidation has emerged as a promising technology for PFAS degradation (Table 4). This method involves applying an electric current to contaminated soils or water, facilitating the breakdown of PFAS molecules. In pilot-scale studies, electrochemical treatment achieved over 90 % degradation of PFOS and PFOA within hours (EPA, 2021c, 2021d). Complementary approaches, such as chemical oxidation using persulfates or ozone, have also shown efficacy, particularly for shorter-chain PFAS (LeBrun, 2024). However, these methods face limitations related to energy costs and secondary byproduct formation, necessitating careful optimization for large-scale applications (Garcia-Segura et al., 2018).

Bioremediation using PFAS-degrading microbes shows significant potential (Table 4). Bacterial strains like *Pseudomonas aeruginosa* and *Acidimicrobium* spp. can degrade specific PFAS under aerobic and anaerobic conditions, though degradation rates are often slow and vary across PFAS types. Phytoremediation, using hyperaccumulator plants like *Populus* species, can sequester PFAS in biomass, reducing soil contamination. Some plants can extract up to 15 % of soil PFAS content over a growth cycle (Parsons et al., 2008). A study in Germany focused

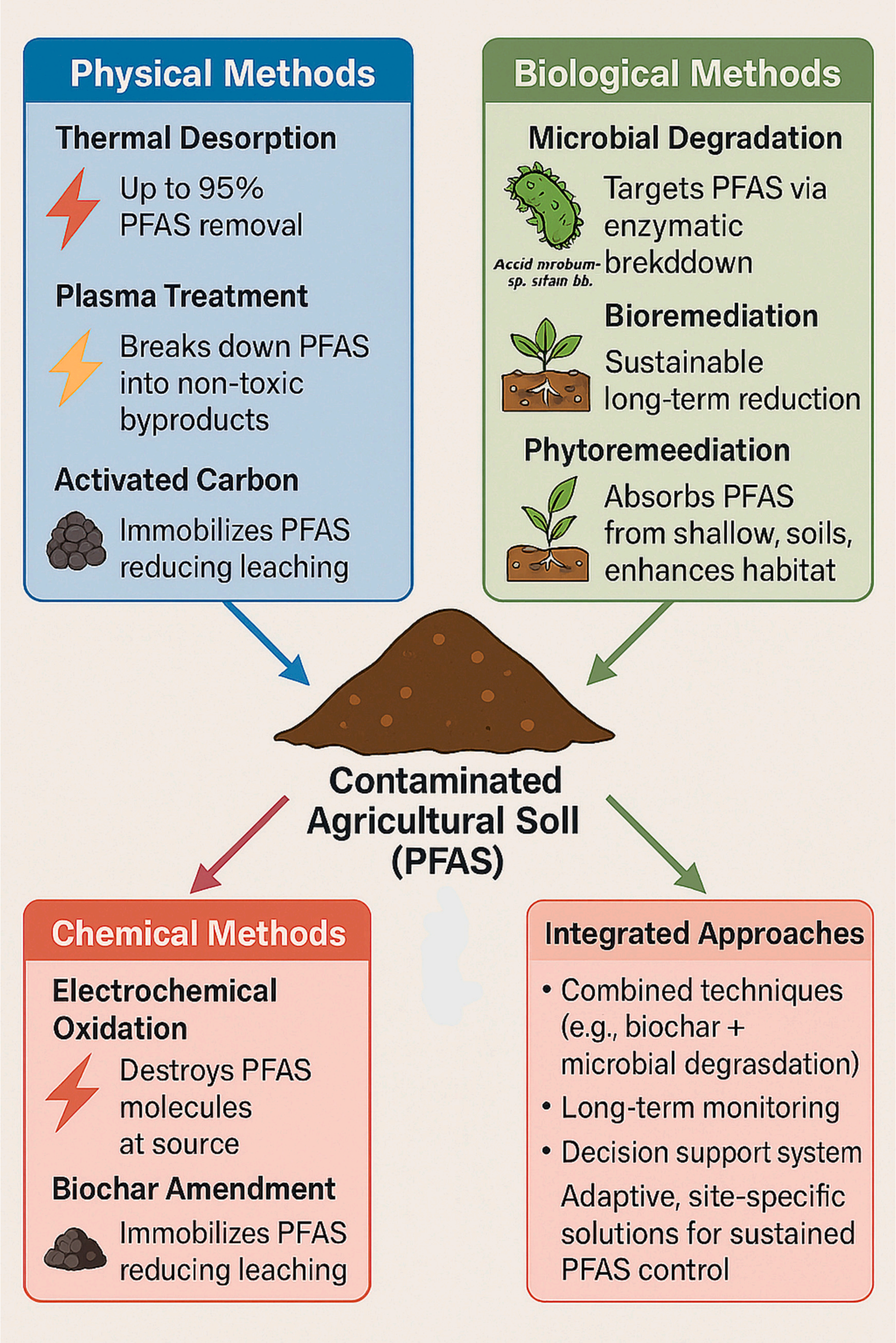

Fig. 5. A comparative chart of remediation techniques.

Table 4
Summary of remediation technique for PFAS in soil.

Remediation technique	Remediation effectiveness	Typical contaminant	Advantages	Limitations	References
Soil amendments and adsorption techniques	Up to 80 % reduction in PFOS leaching	PFOS, PFOA	Cost-effective, environmentally friendly	Requires site-specific customization	Holly et al., 2024; McNamara et al., 2018; Sleep and Juhasz, 2021
Electrochemical and chemical oxidation	Over 90 % degradation of PFOS and PFOA	PFOS, PFOA	Effective for various PFAS types	High energy costs, secondary byproducts	EPA, 2021a, 2021b; Garcia-Segura et al., 2018; LeBrun, 2024
Bioremediation	Up to 31 % degradation of PFOS and PFOA	PFOS, PFOA	Sustainable, long-term solution	Slow degradation rates, variable effectiveness	Conquer Scientific, 2024; Sleep and Juhasz, 2021
Integrated remediation approaches	Up to 70 % reduction in PFAS mobility	PFOS, PFOA	Combines multiple techniques, effective for high-concentration areas	High costs, complex implementation	WSP, 2024; SERDP, 2024a, 2024b; Farmonaut, 2024
Thermal desorption and incineration	Reduction to below detection limits	PFOS, PFOA	Highly effective, complete destruction	Energy-intensive, potential air pollution	Sörengård et al., 2020; WSP, 2024; SERDP, 2024a, 2024b
Plasma treatment	95 % reduction in total PFAS concentrations	PFOS, PFOA	Highly efficient, minimal environmental impact	Scalability and cost-effectiveness need assessment	Drexel University, 2024; SERDP, 2024a, 2024b; EFSA, 2024

on *Pseudomonas aeruginosa* for PFAS degradation in agricultural soils. In lab experiments, this strain degraded 28 % of PFOS and 31 % of PFOA over 90 days, with organic carbon sources like glucose enhancing microbial activity. Although modest, these results suggest bioremediation could be a viable long-term solution, especially with optimized conditions. Further research is needed to assess field effectiveness and scalability (Parsons et al., 2008; Conquer Scientific, 2024; Sleep and Juhasz, 2021).

Thermal desorption and incineration are highly effective for destroying PFAS by heating contaminated soils above 1100 °C, breaking carbon-fluorine bonds (Table 4). Despite their effectiveness, these methods are energy-intensive and can cause air pollution if not managed properly. Advances in low-temperature thermal desorption aim to reduce energy costs and environmental impact. For example, a pilot study in Uppsala, Sweden, treated 50 tons of PFAS-contaminated soil at over 1200 °C, reducing PFOS and PFOA to below detection limits (0.5 μg/kg) in about 6 h per batch, consuming 300 kWh/ton. While effective, high energy demands and costs limit widespread use, but it remains suitable for high-concentration contamination hotspots (Sörengård et al., 2020). The Logan City Biosolids Gasification Project in Australia also used high-temperature combustion to destroy 94 % of persistent organic pollutants, including PFAS, in wastewater streams (WSP, 2024). Additionally, a European pilot study showed that pre-treatment with chemical agents can enhance PFAS removal at lower temperatures (SERDP, 2024a, 2024b).

Integrated remediation approaches combining physical, chemical, and biological techniques offer the most promise for long-term PFAS mitigation (Table 4). For example, a recent case study in Australia combined biochar application with microbial inoculation, achieving a significant reduction in PFAS mobility within one year (WSP, 2024). Similarly, integrating soil washing with advanced filtration systems has been effective in reducing contamination levels in agricultural lands (SERDP, 2024a). Long-term mitigation strategies also include adopting precision agriculture techniques to minimize the inadvertent spread of PFAS through irrigation or fertilization practices (Farmonaut, 2024). Additionally, combining these methods with regular monitoring and adaptive management can enhance their effectiveness. For instance, periodic soil testing and adjusting remediation strategies based on the results can help maintain low PFAS levels over time. Collaborative efforts among researchers, policymakers, and land managers are essential to develop and implement these integrated approaches effectively, ensuring sustainable and long-term solutions for PFAS contamination.

Plasma treatment uses electrical discharge to generate reactive species that degrade PFAS compounds through oxidation (Table 4) and reduction reactions, producing no residual waste and requiring no chemical additions, making it environmentally friendly (Verma et al., 2023). A study in Michigan treated 100 kg of PFAS-contaminated soil with low-temperature plasma, achieving a 95 % reduction in total PFAS concentrations within 2 h, suggesting it could be integrated with existing soil remediation technologies, though further assessment of scalability and cost-effectiveness is needed. While plasma treatment has demonstrated high removal efficiencies up to 95 % for select PFAS compounds such as PFOS under optimized conditions the degradation rate indeed varies depending on molecular structure, chain length, and water matrix (Drexel University, 2024; SERDP, 2024a, 2024b). Table 4 summarizes various PFAS remediation techniques, highlighting their effectiveness, contaminants, advantages, and limitations. Soil amendments and adsorption techniques, like biochar and activated carbon, can reduce PFOS leaching by up to 80 %. Electrochemical and chemical oxidation methods achieve over 90 % degradation of PFOS and PFOA but are energy-intensive and produce byproducts (Singh et al., 2019). Bioremediation using microbes like *Pseudomonas aeruginosa* offers a sustainable long-term solution but has slower degradation rates. Integrated approaches combine multiple techniques, achieving significant PFAS mobility reductions but are complex and costly. Thermal desorption and incineration effectively destroy PFAS at high temperatures but are energy-intensive and may cause air pollution. Plasma treatment shows high efficiency with minimal environmental impact, though its scalability and cost-effectiveness need further assessment.

These remediation techniques offer promising solutions for removing PFAS from contaminated soils. Each method has its strengths and limitations, making it essential to choose the appropriate technique based on site-specific conditions and contamination levels. Combining multiple approaches can enhance overall effectiveness, providing a comprehensive strategy for long-term PFAS mitigation. Continued research and development are crucial to optimize these methods, reduce costs, and ensure their scalability for widespread application. By leveraging these advanced remediation techniques, we can effectively address PFAS contamination and protect environmental and human health.

8. Recommendations and policies for PFAS

8.1. U.S. EPA recommendations

The EPA addresses PFAS contamination in soil and water. As of April 2024, the EPA has established enforceable Maximum Contaminant Levels (MCLs) for six PFAS compounds in drinking water: 4.0 ng/L for PFOA and PFOS, and 10 ng/L for PFHxS, PFNA, and GenX chemicals. (EPA, 2024) For mixtures containing PFHxS, PFNA, HFPO-DA, and PFBS, a Hazard Index of 1 is applied (EPA, 2024). These standards replace the previous 70 ng/L advisory level (EPA, 2016) and are intended to guide PFAS risk assessments and regulatory actions affecting agricultural water use and soil quality. These advisories guide PFAS risk assessments for human health, influencing agricultural water use and soil quality. While there are no specific soil guidelines for PFAS, the EPA encourages local and state agencies to monitor PFAS levels in soils, especially near contamination sites like former military bases and industrial areas. The EPA recommends including PFAS concentrations in broader soil quality assessments, particularly in agricultural areas irrigated with contaminated water or near industrial activity (EPA, 2021a). The EPA's risk assessment framework for PFAS evaluates their mobility and persistence in soils, helping to determine potential human and ecological risks in agricultural settings. This framework provides guidance on monitoring and management practices (EPA, 2021b). Additionally, the EPA has developed resources for soil and water testing protocols for PFAS, including specific methodologies for measuring PFAS in environmental samples. These resources assist farmers, researchers, and policymakers in identifying contamination levels and developing remediation plans (EPA, 2020).

8.2. *U.S. Department of Agriculture (USDA) recommendations*

The U.S. Department of Agriculture (USDA) focuses on ensuring food safety, agricultural sustainability, and public health, with several initiatives addressing the impact of PFAS on agricultural systems. The USDA has provided funding for research related to PFAS in agricultural soils, particularly regarding its uptake by crops and its impact on soil health. This research includes modeling the transport of PFAS in agricultural environments and developing best practices for reducing contamination (USDA, 2024a). In response to PFAS contamination, the USDA encourages the adoption of Agricultural BMPs to reduce the risk of PFAS accumulation in crops and livestock. These practices include sourcing irrigation water from non-contaminated sources, monitoring soils regularly for PFAS contamination, and exploring the use of low-PFAS biosolids (USDA, 2024c). The USDA's Natural Resources Conservation Service (NRCS) works with farmers and landowners to implement soil remediation programs that address PFAS contamination. The NRCS has helped develop guidelines for reducing PFAS levels in contaminated soils through innovative practices, such as the use of bioremediation and soil amendments (USDA, 2024b). These efforts aim to mitigate the impact of PFAS on agricultural productivity and ensure the safety of food products. By supporting research, promoting BMPs, and implementing remediation programs, the USDA plays a crucial role in managing PFAS contamination in agricultural settings (USDA, 2024a). Given the differential bioaccumulation potentials of PFAS across plant species, strategic adjustments to crop planting structures represent a promising avenue for mitigating human and ecological exposure in contaminated agricultural landscapes. Studies have shown that PFAS uptake varies significantly depending on plant physiology, root architecture, and compound-specific properties such as chain length and functional groups. For instance, leafy vegetables and root crops tend to accumulate higher concentrations of PFAS, particularly short-chain variants, due to their greater surface area and direct soil contact. In contrast, certain cereal grains and fibrous crops exhibit comparatively lower accumulation, making them more suitable for cultivation in PFAS-impacted soils. To reduce the risk of PFAS entering the food chain, one viable strategy involves the deliberate planting of non-edible crops—such as bioenergy species (e.g., switchgrass, miscanthus) or fiber crops (e.g., hemp, flax)—in contaminated zones. These crops not only minimize direct human exposure but may also contribute to Phyto stabilization, reducing PFAS mobility and leaching. Alternatively, selecting edible crops with inherently low PFAS uptake, based on empirical accumulation data, can help maintain agricultural productivity while safeguarding food safety. However, the effectiveness of such planting adjustments is contingent upon site-specific factors including PFAS concentration profiles, soil characteristics, irrigation practices, and crop management regimes. Therefore, integrating crop selection with ongoing soil monitoring and risk assessment frameworks is essential for developing adaptive, regionally tailored mitigation strategies. This approach aligns with sustainable land-use planning and offers a practical, low-cost complement to more intensive remediation technologies.

8.3. *European union policies and recommendations*

In Europe, PFAS contamination in agricultural soils is a major concern, and several regulatory measures have been implemented by European agencies to tackle PFAS risks. The EFSA has assessed the risks of PFAS to human health through food consumption, particularly from animal products such as milk, meat, and eggs. It has highlighted the potential for PFAS to accumulate in soils and affect the food chain. EFSA's guidance on PFAS exposure is used by EU member states to regulate PFAS in food products and the environment (EFSA, 2024). The European Commission has adopted regulations that limit PFAS concentrations in surface waters, which indirectly affect agricultural water sources and irrigation practices. The Commission's guidelines require member states to assess PFAS contamination in water bodies that may be used for agricultural irrigation, with the goal of reducing PFAS exposure to crops and soil systems (European Commission, 2024a).

In response to growing concerns about PFAS in soils, the EU has started discussions on setting specific soil quality standards for PFAS. These standards would help establish thresholds for acceptable PFAS concentrations in agricultural soils, providing a regulatory framework for assessing contamination and guiding remediation efforts. The European Commission's proposal aims to reduce PFAS pollution by setting strict limits on discharges of PFAS from industrial and municipal sources (European Commission, 2024b). Under the Integrated Pollution Prevention and Control (IPPC) framework, the EU encourages industrial facilities that use PFAS (e.g., chemical manufacturing plants, textile industries) to reduce emissions to prevent contamination of agricultural soils. This framework includes monitoring and reporting requirements, which support long-term efforts to control PFAS levels in the environment (European Commission, 2024b).

8.4. *Future directions for policy and regulation*

Both U.S. and European authorities are increasing their focus on PFAS regulation, with more comprehensive policies likely to be implemented soon to protect agricultural ecosystems. While there is no federal regulation in the U.S. specifically for PFAS in agricultural soils, states like Michigan and New Jersey are considering their own standards, which could serve as models for federal action and lead to nationwide regulations (EPA, 2021b). The EU's efforts to regulate PFAS in soils are expected to result in mandatory soil testing in agricultural regions and a system for tracking contamination across member states, improving risk management (European Commission, 2024b). Given the global nature of PFAS contamination, there is a growing need for international standards to protect agricultural environments. The U.S. and European countries are collaborating with international organizations like the WHO and UNEP to harmonize PFAS standards globally (WHO, 2022). The EPA, USDA, and European regulatory agencies are making significant strides in developing guidelines to address PFAS contamination in agricultural soils. However, challenges remain in establishing standardized testing, setting thresholds, and ensuring adequate protection for affected agricultural systems. Collaboration among national governments, industry stakeholders, and scientific communities is crucial for mitigating PFAS contamination and ensuring the sustainability of agricultural systems. These policies must reduce PFAS exposure while protecting food security, public health, and the environment for future generations (USDA, 2024a).

9. Conclusion

PFAS contamination in agricultural soils presents a complex and pressing environmental challenge with far-reaching implications for soil health, food safety, and ecosystem sustainability. This review has explored the persistence, mobility, and ecological impacts of PFAS, along with current advances in detection, modeling, and remediation strategies. Despite growing awareness and technological progress, significant gaps remain in understanding the long-term behavior of PFAS in diverse soil environments, particularly under field conditions. Modeling efforts are improving, but they still struggle to account for the chemical diversity of PFAS compounds and the heterogeneity of soil systems. Similarly, while various remediation techniques—ranging from adsorption and oxidation to bioremediation and thermal treatment—have shown promise, their scalability, cost-effectiveness, and environmental trade-offs require further investigation.

Looking ahead, future research should prioritize field-scale validation of laboratory findings, refinement of predictive models to better simulate PFAS transport and degradation, and development of integrated remediation strategies that combine physical, chemical, and biological approaches. Emerging technologies such as plasma treatment, nanomaterials, and advanced oxidation processes offer innovative pathways for PFAS mitigation. Equally important is the advancement of regulatory frameworks and international collaboration to establish harmonized standards and promote knowledge sharing. By aligning scientific innovation with policy development and stakeholder engagement, the global community can work toward sustainable, effective solutions to mitigate PFAS risks in agricultural ecosystems—ensuring long-term protection of soil resources and food systems.

CRediT authorship contribution statement

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