



PFAS: THE PERSISTENT THREAT TO FOOD SAFETY AND PUBLIC HEALTH

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ABSTRACT

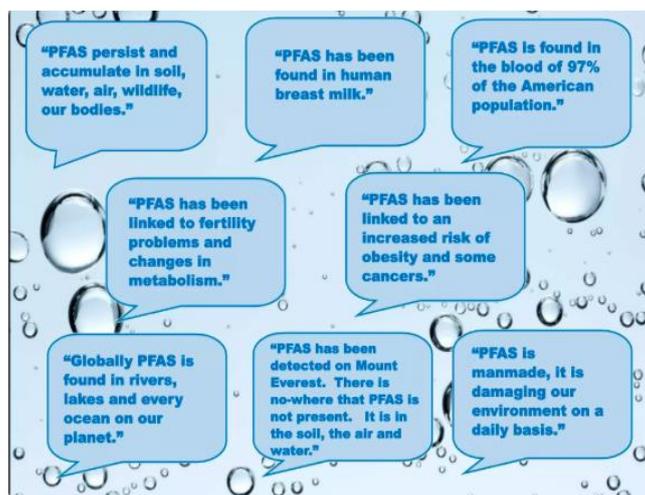
Persistent organic pollutants called per- and poly fluoro alkyl substances (PFAS) are found in common items. They are a serious danger to food security and agricultural sustainability worldwide, especially in Indian farmlands. Biosolid applications, contaminated irrigation water, and industrial discharges are the main sources of contamination. The scope of PFAS contamination, its effects on food security, and creative treatment techniques are all examined in this study. To reduce PFAS contamination while maintaining sustainable farming methods, a multifaceted approach combining detection instruments, cutting-edge remediation technologies, and legislative initiatives is suggested. This review highlights important issues that make it difficult for India to successfully manage PFAS pollution, including legislative inadequacies, insufficient monitoring, and technological obstacles. India's regulatory structure is still in its infancy when compared to other countries' guideline limitations, such as those of the US and the EU, which emphasizes the necessity of thorough monitoring and effective remediation techniques. The need for more research on PFAS source tracking close to industrial and urban centers is highlighted by a systematic gap analysis. To lessen the growing threat of PFAS contamination in India, the findings highlight the necessity of enacting stricter laws, extending monitoring networks, raising stakeholder and public knowledge, and making well-informed policy decisions.

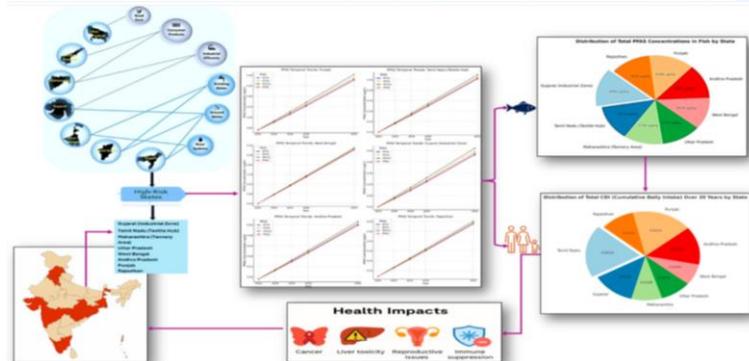
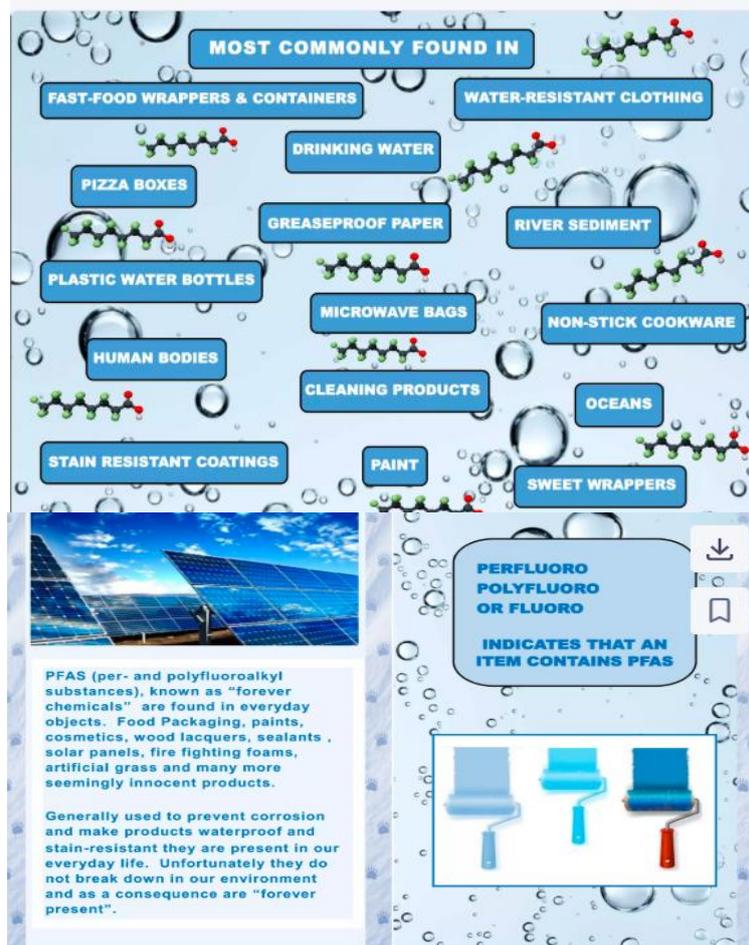
KEYWORDS: PFAS contamination, Bioaccumulation, Fate and transport, remediation technologies, Regulatory standards.

INTRODUCTION

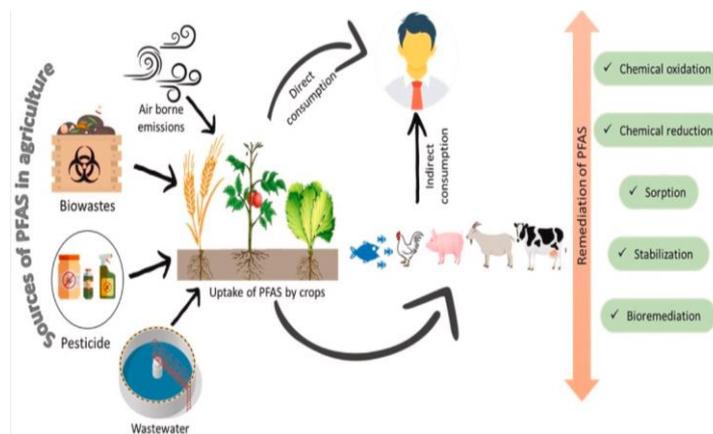
In essence, the existing research focus on laboratory settings leaves a significant knowledge gap regarding the long-term fate and transport of PFAS in the complex and

dynamic natural world. More field-based studies are crucial for developing effective strategies to manage and remediate PFAS contamination.





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PFAS (per- and poly fluoro alkyl substances) exposure is linked to a variety of adverse health effects in humans, including increased risk of some cancers, altered metabolism, and reduced immune function. Specific health concerns include potential links to kidney disease, thyroid issues, and developmental problems, especially in children.

Specific Health Impacts

Immune System

PFAS, particularly PFOA and PFOS, can impair the immune system's ability to fight infections. Studies suggest reduced immune responses to vaccinations in children exposed to PFAS.

Cancer

Increased risk of certain cancers, like kidney cancer, has been associated with PFAS exposure.

Developmental Effects

PFAS can cross the placenta and be transferred through breast milk, leading to early-life exposure. This can affect fetal development and potentially lead to low birth weight and other developmental issues.

Kidney Disease

PFAS exposure is linked to kidney disease and elevated uric acid levels.

Hormonal Disruption

PFAS can disrupt thyroid and reproductive hormone levels, potentially affecting fertility and other bodily functions.

Metabolic Issues

PFAS exposure is associated with altered metabolism and body weight regulation.

Exposure Pathways

Food and Water: PFAS can contaminate food and water sources.

Household Products: PFAS are used in various products like non-stick cookware, food packaging, and firefighting foam.

Occupational Exposure: Workers in industries using PFAS can be exposed.

Indoor Air and Dust: PFAS can be released into the air and dust from treated products.

Ongoing Research

Research is ongoing to understand the full extent of PFAS health impacts and to identify effective strategies for reducing exposure and mitigating risks

FAS and a variety of health effects, including altered immune and thyroid function, liver disease, lipid and insulin dysregulation, kidney disease, adverse

reproductive and developmental outcomes, and cancer. Concordance with experimental animal data exists for many of these effects. However, information on modes of action and adverse outcome pathways must be expanded, and profound differences in PFAS toxicokinetic properties must be considered in understanding differences in responses between the sexes and among species and life stages. With many health effects noted for a relatively few example compounds and hundreds of other PFAS in commerce lacking toxicity data, more contemporary and high-throughput approaches such as read-across, molecular dynamics, and protein modeling are proposed to accelerate the development of toxicity information on emerging and legacy PFAS, individually and as mixtures. In addition, an appropriate degree of precaution, given what is already known from the PFAS examples noted, may be needed to protect human health.

METHODOLOGY

To find published publications on PFAS in agricultural soils, including original research articles and reviews, a thorough search technique was used. The terms "PFAS," "perfluoro," "polyfluoro," and "agriculture" were used to search databases like Scopus, Google Scholar, and Web of Science. 125 research papers, reviews, and reports published between 2010 and 2025 were selected. The Bibliometrix R-Tool was used to combine the search results from all databases and eliminate duplicates (Aria and Cuccurullo, 2017). Works with incomplete data were not included in the analysis. For instance, studies that lacked appropriate methodology, lacked evidence to back up their claims, or provided results that were inconclusive were not deemed suitable for review.

Review of Literature

PFAS Contamination and Its Environmental Impact PFAS are persistent synthetic pollutants that have been widely used across industries due to their chemical stability, heat resistance, and hydrophobic properties. However, these same characteristics contribute to their resistance to degradation and long-term accumulation in the environment (Winchell *et al.*, 2021). PFAS contamination is particularly concerning in European agricultural systems, where pollutants infiltrate soil through biosolid applications, industrial discharge, irrigation with contaminated water, and atmospheric deposition (LazovaBorisova & Adamopoulos, 2024). As a result, PFAS have been detected in farmland soils, hydrological systems, and food chains, raising concerns over long-term ecological and human health impacts (Adamopoulos *et al.*, 2024a). Current research has established that PFAS contamination negatively affects soil fertility, water quality, and agricultural productivity, leading to potential bioaccumulation in crops and livestock (Falandysz *et al.*, 2024). However, despite the growing body of knowledge on PFAS persistence and toxicity, there remains no large-scale, validated soil remediation strategy for agricultural landscapes. Most studies focus on controlled laboratory experiments, leaving major gaps in understanding how PFAS behaves

in dynamic, real-world soil environments (Bolan *et al.*, 2021).

DISCUSSION

Environmental research is increasingly utilizing AI to address PFAS pollution. It is trained with real-world data, can suggest solutions, and supports actionable decisions (Stensson *et al.*, 2023). For instance, AI can estimate PFAS accumulation in human bloodstreams, detect leaching from food packaging, and predict PFAS transportation via air currents (Di Nisio *et al.*, 2022). This collaboration between AI and environmental monitoring and regulatory practice has expanded beyond technical dialogues to developing prototype scenarios demonstrating how AI can be integrated into characterization efforts (Draghi *et al.*, 2024).

Per- and polyfluoroalkyl substances (PFAS) are a vast family of more than 10,000 manufactured organic chemicals known for their versatility in being used as surfactants and repellents. The hydrophobic/lipophobic alkane chain, where the hydrogen atoms are replaced entirely (per-) or partially (poly) by fluorine atoms and a hydrophilic functional group, gives them their unique nature.

These emerging contaminants are persistent in the environment and the human body, causing adverse effects such as liver damage, low infant birth weights, hormonal imbalance, fertility issues, immune system effects, and even cancer Fenton *et al.*, 2021. Due to their ubiquitous nature, PFAS have also been detected in various environmental matrices such as sediment, algae, and animals of Antarctica Gao *et al.*, 2020.

India is a fast-developing country with rapid industrialization and economic development, resulting in increased usage of PFAS due to their extensive applications. Comprehensive information on the production, use, and waste management of PFAS in India is limited Mukherjee Das *et al.*, 2022. A study conducted by Ruan *et al.*, 2019 showed the presence of these forever chemicals in Indian human hair across 14 cities, ranging from < 0.02 ng/g to 3.78 ng/g.

The aim of the present study was both quantitative and qualitative detection of these persistent chemicals in the waters of the metropolitan city of 'Chennai' in the Indian state of Tamil Nadu. This work is unique in terms of thorough sampling that includes ground and surface water sources contaminated by the leachate from an open dump site and untreated domestic wastewater discharge, respectively. Additionally, samples were included from every stage of a significant water treatment plant where the raw water is sourced from a lake surrounded by industries. Various sampling sites were selected to capture different geographical locations and potential PFAS sources.

Biological remediation methods

Biological remediation is considered the most efficient, cost-effective, and environmentally friendly approach compared to other remediation strategies. Bioremediation involves breaking down, transforming, removing, or immobilizing contaminants through the metabolic activity of living organisms. Its primary goal is to degrade or convert pollutants into less toxic forms. This technique has been successfully applied to eliminate organic pollutants such as polycyclic aromatic hydrocarbons, gasoline, and pesticides. However, significant knowledge gaps remain regarding biological remediation of PFAS (Biswas and Goel, 2022; Kucharzyk *et al.*, 2017).

One of the primary challenges in PFAS biodegradation is the strength of the carbon-fluorine (C-F) bond, which makes these compounds highly resistant to microbial breakdown, requiring high energy to initiate degradation. Microorganisms are unable to utilize the fluorine-saturated carbon chain as an energy source due to the formation of a hydrophobic barrier around carbon-carbon (C-C) bonds and the absence of hydrogen atoms in the PFAS alkyl chain (Rayne and Forest, 2009). Some bacterial species, such as *Pseudomonas* sp., have demonstrated significant PFAS bioaccumulation under aerobic conditions, though to a much lesser extent in anaerobic environments. However, to date, no verified reports confirm the microbial removal of fluorine atoms from PFAS.

Phytoremediation, a plant-based remediation technique, involves the uptake and sequestration of contaminants, thereby reducing their bioavailability in soil (Bolan *et al.*, 2022). For instance, one study reported that individual PFAS were removed by up to 96 % through plant uptake in a full-scale tropical constructed wetland (Yin *et al.*, 2017). Another study examined the uptake and accumulation of seven PFAS by the wetland species *Juncus effusus*, reporting a removal efficiency of 11.4 % (mass basis) from solution for spiked PFAS (W. Zhang *et al.*, 2019c).

Similarly, plants at a firefighting site near Stockholm, Sweden, were found to have accumulated 26 PFAS compounds (Gobelius *et al.*, 2017). Herbaceous species such as *Amaranthus tricolor*, *Equisetum hyemale*, and *Schedonorus arundinaceus* exhibited above-average accumulation of multiple PFAS substances. Additionally, tree species like *Fraxinus pennsylvanica*, *Liquidambar styraciflua*, and *Betula nigra* have shown some capacity for PFAS accumulation in woody tissues. However, field studies are essential to verify the practicality of phytoremediation in remediating PFAS-contaminated soil, particularly regarding the excretion and potential release of PFAS from plants.

Despite its environmental and economic advantages, biological remediation faces notable challenges in treating PFAS-contaminated soils. The chemical stability

of the C-F bond significantly limits microbial degradation, hindering complete removal (Beškoski et al., 2024; Shahsavari et al., 2021). Although phytoremediation facilitates PFAS uptake, improper disposal of contaminated plants poses a risk of introducing PFAS into the food chain. Furthermore, PFAS's bioaccumulative nature adds complexity, as sequestered compounds may lead to secondary contamination, necessitating careful management to prevent unintended environmental consequences (Beškoski et al., 2024).

The effectiveness of bioremediation also depends on site-specific factors, including soil pH, organic matter content, and co-contaminants, which influence PFAS bioavailability and microbial activity (Gu, 2024; Sleep and Juhasz, 2021). Additionally, over time, PFAS sequestration in soil reduces microbial accessibility, further complicating degradation (Gu, 2024). Limited availability of effective PFAS-degrading microorganisms and discrepancies between laboratory and field conditions present additional hurdles (Romantschuk et al., 2023). To overcome these challenges, hybrid approaches integrating biological, chemical, or physical treatments may be necessary. Advances in microbial engineering could enhance degradation rates and minimize the formation of incomplete breakdown by-products (Nguyen et al., 2023).

Environmental significance

The limited understanding of PFAS accumulation in agricultural soils raises concerns about their potential uptake by livestock, crops, and food sources, which could pose health risks to consumers. The presence of PFAS in agricultural soils, crops, water sources, and food products necessitates a comprehensive understanding of their sources, uptake mechanisms, ecological impacts, and remediation strategies. Effectively addressing PFAS contamination is essential to safeguarding food safety, ecosystem integrity, and public health. This review serves as a guideline for future research aimed at mitigating PFAS risks in agricultural systems.

CONCLUSION

It is imperative that PFAS poisoning in communities and the environment be addressed. The potential of AI technology for environmental study is enormous.

An effective reaction requires the use of top-down laws, cross-disciplinary monitoring systems, and analytical and corrective instruments. In decision-making processes, cooperation, democratic participation, and impacted communities' self-management are essential. The revolutionary potential of these technologies in addressing PFAS contamination is highlighted by the speed at which AI is developing. Addressing PFAS pollution, which presents a serious environmental risk to food security and agricultural sustainability, is a major public health concern in Europe. These "forever

chemicals" endanger food systems and public health by building up in crops, livestock, soil, and water.

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