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# The impact of PFAS on the public health and safety of future food supply in Europe: Challenges and AI technologies solutions of environmental sustainability

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**ABSTRACT**

Per- and polyfluoroalkyl substances (PFAS) are persistent organic pollutants extensively used in industrial and consumer applications. Their accumulation in European agricultural soils through industrial discharges, biosolid applications, and contaminated irrigation water poses an unprecedented threat to food security, soil health, and water quality. Despite extensive laboratory research, no full-scale, long-term validated PFAS soil remediation study exists, leaving critical gaps in mitigation strategies. Existing approaches–including mobilization, immobilization, and degradation techniques–have demonstrated effectiveness in controlled environments but lack real-world validation in dynamic agricultural settings. This study proposes an artificial intelligence (AI)-driven remediation framework that integrates real-time detection tools, predictive modeling, and adaptive remediation technologies to overcome these challenges. Unlike static remediation strategies, the proposed AI-assisted system dynamically optimizes remediation interventions based on contamination patterns, soil composition, and environmental conditions. Machine learning algorithms and statistical models enable precise contamination tracking, predictive PFAS migration modeling, and automated remediation decision-making, offering a scalable and responsive solution for sustainable agricultural management. This study underscores the urgent need for large-scale, policy-backed field trials to validate AI-driven PFAS remediation technologies, bridging the gap between scientific advancements and real-world implementation. By transitioning AI-assisted mitigation from theory to an adaptive, field-deployable framework, this research ensures scalable solutions for sustainable food security, environmental resilience, and long-term public health protection.

**Keywords:** PFAS contamination, agricultural sustainability, food security, AI technologies, community engagement, environmental health, soil restoration, public health, Europe

## INTRODUCTION

Per- and polyfluoroalkyl substances (PFAS) are synthetic pollutants widely used in industrial and consumer products due to their chemical stability, heat resistance, and hydrophobic properties. However, their persistence in the environment has led to widespread contamination, posing a severe threat to agricultural sustainability, food security, and public health. PFAS compounds are now detected in soil, groundwater, and the food chain, leading to significant concerns over long-term ecological and human health risks (Sivagami et al., 2023; Winchell et al., 2021). Despite growing scientific awareness, no full-scale, long-term validated PFAS soil remediation study exists, leaving critical gaps in mitigation strategies (Falandysz et al., 2024). While traditional adsorption-based techniques have been explored, recent advances in selective adsorption technologies have shown promise in PFAS remediation, with enhanced contaminant capture and retention. These materials leverage surface modifications and site-specific tuning to improve adsorption performance, particularly in complex soil environments. Since their introduction in the mid-20$^{th}$ century, PFAS have been extensively used in nonstick cookware, firefighting foams, textiles, and food packaging. While technological advancements have improved PFAS detection, research on effective, real-world remediation strategies remains insufficient (Said & El Zokm, 2024; Sivagami et al., 2023). The lack of large-scale studies has hindered the development of science-backed regulatory policies, resulting in ongoing contamination in farmlands, drinking water sources, and ecosystems (Lazova-Borisova & Adamopoulos, 2024).

### Regulatory & Environmental Gaps

Historically, PFAS received little regulatory scrutiny, allowing contamination to spread unchecked (Prasad & Elchuri, 2023). However, increasing awareness has escalated PFAS into a global environmental and geopolitical issue, particularly regarding the right to clean food and water (Adamopoulos et al., 2024b; Peritore et al., 2023). Many European regions with intensive agriculture and industrial activity are now PFAS contamination hotspots, affecting soil fertility, water quality, and livestock health (Adamopoulos et al., 2024a). Despite extensive research on PFAS ecotoxicology (Koulini et al., 2024), existing remediation strategies–including soil washing, thermal treatment, and chemical oxidation–lack full-scale field validation. Current approaches often fail to address long-term contamination risks (Adamopoulos et al., 2023a), including PFAS re-release into the environment through leaching, bioaccumulation, and soil-bound persistence (Bolan et al., 2021).

### Artificial Intelligence as a Game-Changer in PFAS Management

While artificial intelligence (AI) has been applied in pollution monitoring and environmental modeling, its direct application in PFAS soil remediation remains largely unexplored, particularly in large-scale agricultural settings (Giesy & Kannan, 2001; Winchell et al., 2022). This study addresses this critical gap by developing an AI-assisted remediation framework that integrates real-time contamination mapping, predictive PFAS migration modeling, and adaptive remediation interventions based on site-specific factors. Unlike static remediation models, our AI-driven system dynamically adjusts to contamination levels, optimizing remediation strategies in real time. This approach bridges the gap between AI-assisted environmental monitoring and active, data-driven PFAS mitigation, making it one of the first studies to propose a scalable AI-powered framework for PFAS soil remediation. By translating AI from theoretical environmental assessments to real-world field implementation, this research advances the state of the art in PFAS mitigation. Big Tech companies, research institutions, and policymakers must collaborate to integrate AI-driven environmental monitoring and sustainable remediation models into legislative frameworks (Chen et al., 2023; Ditria et al., 2022). The intersection of AI, environmental science, and regulatory policy is critical to addressing PFAS contamination at scale, preventing further degradation of Europe's agricultural lands and water systems.

### Aims and Scope

This study investigates the scale, risks, and challenges associated with PFAS contamination in European agricultural systems, focusing on its effects on soil health, water resources, and food security. It critically evaluates current remediation technologies and highlights the absence of large-scale validated studies, which limits policy enforcement and long-term environmental sustainability. By integrating scientific research, case studies, and AI-driven methodologies, this study proposes a comprehensive strategy aligning with the European green deal and the chemical strategy for sustainability (CSS).

### Objectives

1. Identify and quantify PFAS contamination pathways in European agricultural systems, particularly from industrial discharges, biosolids, and contaminated irrigation water.
2. Evaluate the limitations of existing PFAS remediation strategies–including mobilization, immobilization, and degradation techniques–by assessing their effectiveness and scalability in real-world agricultural settings.
3. Develop an AI-integrated remediation framework that combines real-time contamination mapping, predictive PFAS migration modeling, and adaptive remediation interventions.
4. Bridge the gap between research and policy implementation by aligning AI-driven remediation solutions with European regulatory frameworks, including the European green deal and the CSS.
5. Assess the economic and environmental feasibility of large-scale AI-assisted PFAS remediation, considering long-term impacts on soil health, food security, and public health.

## LITERATURE REVIEW

### 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 (Sivagami et al., 2023; 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 (Lazova-Borisova & 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).

## Existing PFAS Remediation Strategies and Their Limitations

Research has explored various strategies to mitigate PFAS contamination in soils, which generally fall into three categories: mobilization and extraction, immobilization, and degradation methods. Mobilization techniques, such as soil washing and phytoremediation, aim to extract PFAS from contaminated soil, but concerns persist regarding recontamination through leaching and incomplete removal (Cousins et al., 2016). Similarly, immobilization strategies, which rely on sorption using activated carbon, biochar, or clay minerals, have been shown to reduce PFAS mobility but do not eliminate the contaminants from the environment (Ahrens & Bundschuh, 2014; EFSA, 2020). Recent advancements in next-generation adsorption materials have demonstrated enhanced capture efficiency and selectivity, improving PFAS retention while maintaining soil integrity. These materials can be tailored to address specific contamination challenges, overcoming key limitations seen in conventional immobilization approaches. In addition, thermal and chemical destruction methods, such as high-temperature incineration or in-situ chemical oxidation, have proven effective in laboratory conditions but are cost-prohibitive and impractical for large-scale agricultural sites (Kottohoff et al., 2015; OECD, 2021). A major limitation of existing studies is the lack of long-term validation for remediation techniques under field conditions. Laboratory results often fail to account for complex environmental variables, including soil composition, microbial interactions, and seasonal changes in groundwater flow (Bolan et al., 2021; Scheringer et al., 2014). Furthermore, economic constraints have limited the widespread application of thermal oxidation and chemical degradation methods, leaving no scalable or financially viable PFAS soil remediation strategy for agricultural lands.

## Regulatory and Policy Gaps in PFAS Management

While research on PFAS ecotoxicology has expanded significantly, regulatory responses remain fragmented. Historically, PFAS have received limited regulatory oversight, resulting in unchecked contamination and delayed intervention in agricultural and industrial zones (Prasad & Elchuri, 2023). As awareness grows, geopolitical disputes over clean food and water rights have intensified, further complicating PFAS management strategies (Adamopoulos et al., 2024b; Peritore et al., 2023). Many European regions with intensive agriculture and industrial activity now face contamination crises, yet governments lack enforceable policies for large-scale remediation efforts (Lazova-Borisova & Adamopoulos, 2024). Inconsistent regulatory enforcement has also led to delayed adoption of innovative remediation technologies, particularly in cases where scientific research has not yet been translated into policy-backed action. Without a structured regulatory framework mandating systematic PFAS monitoring and large-scale cleanup projects, soil and water contamination will continue to escalate, further endangering food security (Bolan et al., 2021).

## AI and Predictive Technologies as a New Approach to PFAS Remediation

AI and machine learning offer unparalleled potential in enhancing PFAS monitoring and remediation efforts. While AI has already been successfully applied in climate modeling, pollution tracking, and waste management, its integration into PFAS mitigation remains underexplored (Gerardu et al., 2023; Mijwil et al., 2024). Emerging AI-driven tools have demonstrated the ability to map contamination hotspots, predict PFAS migration patterns, and optimize remediation strategies based on real-time data (Ditria et al., 2022). Advances in AI-assisted sorption technologies have shown promise in enhancing remediation efficiency, particularly by refining material deployment strategies based on site-specific contamination profiles. Additionally, AI-driven monitoring frameworks can track adsorption performance over time, helping to predict saturation thresholds and inform necessary remediation adjustments (Shivaprakash et al., 2022). Recent studies suggest that AI-powered remote sensing technologies and spectral analysis could significantly improve early detection of PFAS in agricultural soils. Machine learning models have also been used to analyze historical contamination trends, allowing researchers to predict future PFAS migration pathways (Bibri et al., 2024). Additionally, AI-assisted simulations have shown potential for evaluating the effectiveness of remediation techniques, enabling researchers to design cost-effective and site-specific solutions for PFAS removal (Chen et al., 2023). Despite these advancements, the application of AI in PFAS remediation remains largely theoretical. While AI-based approaches hold promise in automating contamination risk assessment and optimizing remediation decisions (Navidpour et al., 2024; Valamontes, 2024), there is a lack of real-world implementation studies demonstrating their efficacy in large-scale environmental remediation projects (Bibri et al., 2024; Winchell et al., 2022). The next step in PFAS research must involve bridging the gap between AI-driven environmental monitoring and field-based remediation trials to develop scalable, adaptive solutions.

## The Need for an Integrated, Policy-Backed Strategy

The current state of PFAS research highlights a disconnect between scientific advancements, regulatory enforcement, and technological applications. While existing studies have extensively characterized PFAS contamination and its risks, no large-scale remediation projects have been executed to validate field-level effectiveness. Addressing PFAS contamination requires an integrated approach that combines scientific research, policy intervention, and AI-driven technological advancements. Without a coordinated response, PFAS will continue to accumulate in agricultural soils, infiltrate food systems, and pose long-term risks to human health. This study aims to fill this critical gap by proposing a multi-disciplinary strategy that leverages AI-assisted remediation frameworks, regulatory enforcement, and scalable soil treatment solutions. By aligning research with European Union (EU) sustainability goals, this paper seeks to establish a roadmap for large-scale, real-world PFAS remediation trials, bridging the gap between theory and practice.

# METHODS AND MATERIALS

## Current State of PFAS Contamination in Europe: Sources of Contamination

Understanding the sources of PFAS contamination is critical for targeted remediation and policy development. In Europe, these sources primarily include as follows.

### *Industrial emissions*

The manufacturing of textiles, firefighting foam, nonstick cookware, and other PFAS-based products introduces these chemicals into the environment. Industrial facilities involved in their production often discharge untreated wastewater, leading to PFAS contamination in nearby water bodies and soil. Studies have reported elevated PFAS levels in regions surrounding chemical manufacturing plants, particularly in Belgium and Germany. These emissions often lead to persistent contamination of nearby agricultural lands due to surface runoff and atmospheric deposition.

### *Agricultural practices*

**Biosolids and fertilizers:** The application of biosolids (treated sewage sludge) to agricultural lands is a significant contributor. Wastewater treatment processes tend to concentrate PFAS, resulting in biosolids with elevated contamination levels. When applied to agricultural land, these biosolids introduce PFAS into the soil, where the chemicals can leach into crops and groundwater.

**Contaminated irrigation water:** Many European rivers, including the Rhine and Seine, have been identified as carrying PFAS contamination from industrial discharges upstream. When farmers use these water sources for irrigation, PFAS are transferred into the soil and taken up by plants.

### *Waste mismanagement*

Improper disposal of PFAS-containing products exacerbates the problem. Landfills without adequate lining and leachate collection systems allow PFAS to seep into the ground. Incineration of PFAS products at suboptimal temperatures can release them into the atmosphere, where they return to the soil and water through precipitation.

**The European green deal:** The European green deal, adopted in 2019, aims to make the EU climate-neutral by 2050 while addressing pollution and sustainability issues across industries. PFAS contamination, particularly in agricultural and water systems, has been identified as a key priority under its zero-pollution ambition. Key elements include the following.

*CSS:* The CSS within the European green deal outlines stricter controls on harmful chemicals, including PFAS. The strategy prioritizes eliminating non-essential PFAS uses and reducing their prevalence in consumer and industrial products (European Commission, 2020).

*Circular economic action plan:* This initiative seeks to reduce PFAS in waste streams to prevent reintroduction into the environment, especially in agriculture, where biosolids may contain PFAS.

*Zero pollution action plan:* This plan targets contamination hotspots and includes funding for PFAS research and mitigation technologies, particularly in vulnerable ecosystems like farmland and water sources.

**Gaps in implementation**

*Insufficient monitoring*: Existing monitoring networks often fail to capture PFAS hotspots in rural or agricultural regions, which are most affected.

*Lack of coordination:* Member states implement the European green deal Deal objectives at varying speeds, resulting in inconsistent PFAS mitigation strategies across borders (Goldenman et al., 2019).

**The REACH regulation**

Registration, evaluation, authorization, and restriction of chemicals (REACH) regulation is one of the EU's most comprehensive chemical control policies. Under REACH, several PFAS chemicals, including perfluorooctanoic acid (PFOA) and its salts, have been restricted or banned (European Chemicals Agency [ECHA], 2020). Recent proposals aim to broaden restrictions to cover all non-essential PFAS uses across industries.

**Key achievements**

*Regulatory control:* The listing of certain PFAS as substances of very high concern has significantly reduced their production and import within the EU.

*PFAS restriction proposal:* A joint effort by Germany, Denmark, the Netherlands, Norway, and Sweden seeks to impose a group-wide restriction on PFAS under REACH, a landmark step toward comprehensive regulation (ECHA, 2020).

**Challenges in enforcement**

*Limited resources:* Many member states lack the technical capacity and financial resources to enforce REACH regulations effectively in agricultural areas.

*Data gaps:* Monitoring and reporting of PFAS concentrations in agricultural soils, water, and crops remain inconsistent, complicating enforcement efforts (Vierke et al., 2012).

**Future directions**

*Harmonized monitoring:* Develop an EU-wide network of PFAS monitoring stations with standardized protocols to identify hotspots in real time.

*Funding for innovation:* Increase funding for research into advanced PFAS remediation technologies, such as plasma-based and electrochemical methods, to enable scalable solutions for farmlands (Zhao, 2018).

*Community engagement:* Incorporate local farmers and communities into PFAS monitoring programs to enhance data collection and raise awareness. While the European green deal and REACH regulation represent commendable steps toward mitigating PFAS contamination, a more coordinated and aggressive approach is necessary to address challenges in agricultural contexts. Enhancing monitoring infrastructure, harmonizing regulatory thresholds, and investing in scalable solutions are essential for safeguarding Europe's food supply and ecological health.

**Extent of contamination:** Scientific studies have highlighted alarming levels of PFAS in European agricultural hotspots.

**Geographic hotspots**

*Belgium and the Netherlands:* Soils near industrial sites such as 3M facilities have shown PFAS concentrations exceeding 1,000 ng/kg.

*Italy:* Agricultural areas near Vicenza report PFAS contamination in rice and vegetables due to groundwater pollution.

*Scandinavian countries:* Despite strict environmental regulations, regions with biosolid applications have measurable PFAS in grazing fields.

**Bioaccumulation in crops and water sources:** Studies confirm that PFAS readily accumulates in crops like wheat, rice, and leafy vegetables, particularly in acidic soils, where its mobility is enhanced. Livestock drinking contaminated water also bioaccumulates PFAS, transferring them to dairy and meat products.

## Methodology

### *Innovative mathematical modeling for PFAS spread*

To predict the extent of PFAS contamination in agricultural lands, we propose a contaminant transport and bioaccumulation algorithm that integrates.

**Diffusion-advection** equation for PFAS migration in soil:

$$\frac{\partial C}{\partial t} = D\nabla^2 C - \vec{v}\cdot\nabla C - kC, \tag{1}$$

where $C$ is PFAS concentration, $D$ is diffusion coefficient, $\vec{v}$ is advection velocity (water flow), and $k$ is degradation rate (assumed negligible for PFAS due to persistence).

**Bioaccumulation index** (BAI) to estimate PFAS uptake in crops:

$$BAI = \frac{C_{plant}}{C_{soil}}, \tag{2}$$

where $C_{plant}$ is PFAS concentration in plant tissues and $C_{soil}$ is PFAS concentration in soil.

**Risk factor** (RF) combining contamination and exposure probabilities:

$$F = P_C \times P_E \times \frac{1}{L_T}, \tag{3}$$

where $P_C$ is contamination probability, $P_E$ is exposure likelihood (human or ecological), and $L_T$ is latency threshold for health effects.

This algorithm can guide policy and remediation by identifying high-risk zones and prioritizing intervention strategies.

### *Detailed modeling approach*

**Appendix A** provides mathematical formulations, computational frameworks, and assumptions underlying the modeling approach for PFAS transport, bioaccumulation, and risk assessment described in the main text. **Appendix B** shows visual representation of PFAS contamination and mitigation.

### *Contaminant transport in soil and water*

**Diffusion-advection** equation:

$$C\frac{\partial C}{\partial t} = D\nabla^2 C - \vec{v}\cdot\nabla C - kC, \tag{4}$$

where *C (x, y, z, t)* is PFAS concentration in soil or water at location *(x, y, z)* and time *t*, *D* is diffusion coefficient ($m^2/s$), $\nabla^2 C$ is Laplacian operator describing diffusion, $\vec{v}$ is advection velocity vector (*m/s*), and *k* is decay constant (*/s*).

**Boundary conditions**

1. Surface boundary (*z = 0z = 0*): PFAS concentration is highest at the $C(x,y,0,t) = C_{source}e^{\frac{-t}{t_{release}}}$, where $t_{release}$ is the time for PFAS release.
2. Groundwater interaction ($z = z_{gw}$): PFAS mixing with groundwater. $\frac{\partial C}{\partial z}[\backslash bigg|?]_{z=z_{gw}} = 0\ (no\ flux\ across\ boundary)$.
3. Domain edges (x, yx, y boundaries): $C(x_{edge}, y_{edge}, z, t) = 0\ (open\ system)$.

*Numerical implementation:* The finite difference method (FDM) is used to approximate spatial derivatives. For instance, the Laplacian term in 1D: $\nabla^2 C \approx \frac{C_{i-1} - 2C_i + C_{i+1}}{\Delta x^2}$.

### *Bioaccumulation in crops*

*BAI*

$BAI = \frac{C_{plant}}{C_{soil}}[\backslash tag?]$, where $C_{plant}$ is PFAS concentration in plant tissues and $C_{soil}$ is PFAS concentration in the root zone.

*Partition coefficients:* The plant uptake model uses soil-to-root ($K_{soil\text{-}root}$) and root-to-shoot ($K_{root\text{-}shoot}$) coefficients: $C_{plant} = K_{soil-root} \times C_{soil} \times K_{root-shoot}$.

Typical values for $K_{soil\text{-}root}$ and $K_{root\text{-}shoot}$ are derived from experimental data.

*Crop-specific uptake:* Adjust $K_{soil\text{-}root}$ and $K_{root\text{-}shoot}$ as K_{\text{root-shoot}} based on crop type:

- Leafy vegetables: High $K_{root\text{-}shoot}$
- Root vegetables: High $K_{soil\text{-}root}$

### *Risk assessment model*

**RF**

$RF = P_C \times P_E \times \frac{1}{L_T}$ where $P_C$ is probability of contamination, $P_E$ is exposure probability, and $L_T$ is latency threshold (time before observable health impacts).

**Probability components**

1. $P_C$ is based on contamination levels from transport models: $P_C\ \frac{C_{soil}}{C_{threshold}}$, where is $C_{threshold}$ is the regulatory limit for PFAS in soil.
2. $P_E$ is exposure likelihood considering human or ecological interactions:$P_E = \frac{Exposure\ route\ activity}{Total\ activity}$.
3. $L_T$ is estimated from toxicological studies of PFAS.

### *Sensitivity analysis*

Sensitivity analysis is performed by varying critical parameters:

1. Diffusion coefficient (*D*):

- Range: $10^{-6}$ to $10^{-9}$ $m^2/s$
- Impact: Faster or slower PFAS spread.

2. Advection velocity ($\vec{v}$):
   - Range: 0.01 to 1.0 m/s
   - Impact: Directional PFAS migration.
3. Uptake coefficients ($K_{soil\text{-}root}$ and $K_{root\text{-}shoot}$):
   - Adjust for crop type and soil conditions.

### *Computational framework*

**Python implementation overview:**

1. Transport simulation:
   - Define spatial domain ($L_x$, $L_y$, $L_z$) and grid resolution ($N_x$, $N_y$, $N_z$) .
   - Apply FDM for spatial derivatives.
2. Bioaccumulation prediction:
   - Link $C_{soil}$ from transport model to $tC_{plant}$.
3. Risk mapping:
   - Use GIS tools to visualize RFRF spatially.

### *Validation and case studies*

- Validation data from European farmlands (e.g., PFAS hotspots in Belgium and Italy).
- Compare modeled concentrations ($C_{soil}$ and $C_{plant}$) with measured values.
- Use case studies to refine parameters and verify accuracy.

## Comparative Analyses Across Europe

Comparative studies have highlighted the adaptability of plasma-based and phytoremediation techniques to diverse soil types and climatic conditions across Europe. Key findings include the following.

### *Plasma-based remediation*

- **Soil type suitability:** Effective in sandy and loamy soils, where PFAS mobility is higher.
- **Climate considerations:** High humidity levels in temperate climates enhance the efficiency of plasma-generated reactive species.
- **Scalability:** Plasma systems can be adapted for mobile units, enabling in-situ treatment in remote areas.

### *Phytoremediation*

- **Soil type suitability:** Performs well in organic-rich soils, which support robust plant growth.
- **Long-term benefits:**
  - Restores soil ecosystems while reducing PFAS levels.
  - Provides additional economic benefits through biomass production for energy or other uses.

## Challenges and Recommendations

While the pilot projects demonstrate promising results, challenges remain:

1. **Scalability:** Adapting these technologies for large-scale contamination requires significant investment.
2. **Timeframes:** Phytoremediation is slower than other techniques, making it less suitable for urgent remediation needs.
3. **Integration of methods:** Combining techniques, such as plasma remediation with adsorption or phytoremediation with bioaugmentation, yields better results but increases complexity.

# RESULTS

## Impact on the Future Food Supply

PFAS contamination poses a multifaceted threat to Europe's food supply chain, affecting crop yields, livestock quality, and economic stability. The persistent nature of PFAS in soil and water exacerbates these issues, creating long-term challenges for sustainable agriculture and food security. **Table 1** shows PFAS bioaccumulation in crops and livestock.

### *Bioaccumulation in crops*

PFAS infiltrates plants primarily through uptake from contaminated soil and irrigation water. This process depends on several factors, including soil composition, water quality, and plant physiology.

**Mechanisms of PFAS uptake**

*Soil-to-root transfer*: PFAS binds to soil particles, but some remain in pore water, where plant roots take them up.

*Translocation to edible parts:* PFAS molecules move from roots to shoots and accumulate in leaves, grains, and fruits, with varying degrees depending on the plant type.

*Impact on nutritional value and yield:* Studies indicate that elevated PFAS levels reduce plant growth and photosynthetic efficiency, leading to lower crop yields (Ghisi et al., 2019). For instance, in wheat, PFAS exposure decreased grain size and protein content by up to 20%. In leafy vegetables like lettuce, PFAS reduced chlorophyll content, stunting growth by approximately 15%.

**Table 1.** PFAS bioaccumulation in crops and livestock

| Category | PFAS uptake pathways | Impacts on yield/quality | Economic impact | Data source |
|---|---|---|---|---|
| Crops | Soil-to-root transfer & irrigation water | Reduced grain size (20%) & lower protein content | Loss of income from reduced yield | Ghisi et al. (2019) |
| Dairy | Contaminated feed & water | Elevated PFAS levels in milk & export restrictions | Market losses from unsellable products | Göckener (2020) |
| Meat | Feed & water contamination | Muscle tissue contamination & health risks to consumers | Decreased market demand | Goldenman et al. (2019) |
| Eggs | PFAS in poultry feed | High PFAS concentration in eggs | Regulatory non-compliance fines | EFSA (2020) |

**Livestock contamination**

Livestock exposed to PFAS-contaminated feed or water exhibits significant bioaccumulation in their tissues, milk, and eggs.

**Pathways of exposure**

*Ingestion of contaminated feed:* Crops grown in PFAS-affected soil introduce these chemicals into animal diets.

*Water contamination:* PFAS in drinking water further contributes to accumulation in animals.

**Consequences for livestock products**

*Milk:* PFAS levels in milk can exceed safety thresholds, leading to market restrictions (Göckener, 2020).

*Meat:* Muscle tissues retain PFAS, particularly long-chain compounds, reducing their safety for consumption.

*Eggs:* High PFAS levels in poultry feed translate into significant contamination in eggs.

**Economic implications:** PFAS contamination imposes both direct and indirect economic costs, undermining agricultural sustainability and market competitiveness.

*Reduced agricultural productivity*

- Lower crop yields due to PFAS-induced growth inhibition.
- Decreased livestock productivity from health impacts, including reduced milk and egg yields.

*Remediation and compliance costs*

- Farmers face high costs to remediate contaminated soil and water sources.
- Complying with stricter safety standards for PFAS in food products adds further financial burdens.

*Healthcare expenditures*

- Increased public health costs arise from exposure to PFAS-contaminated food linked to conditions such as cancer, thyroid disorders, and developmental issues (Goldenman et al., 2019).

**Data representation**

*Data source:* Studies have shown associations between PFAS exposure and health issues such as increased cholesterol levels, thyroid disease, and certain cancers.

PFAS levels in human blood across regions data source

**The PFAS exposure data comes from multiple authoritative sources**

*Agency for toxic substances and disease registry (ATSDR, 2020):*

- Conducted PFAS exposure assessments in highly contaminated regions across the USA, such as Parkersburg, West Virginia, where chemical manufacturing facilities have operated for decades.

*National Institute of Health (ISS), Italy*

- Focused on the Veneto Region, known for widespread PFAS contamination due to industrial discharges into water systems.

*Greek National Organization for the Provision of Health Services (EOPYY)*

- Reported elevated PFAS levels among Greek populations, identifying age-specific vulnerabilities in children, adolescents, adults, and the elderly.

**Table 2** shows the prevalence of health conditions linked to PFAS exposure. **Table 3** shows the data of perfluorooctane sulfonate (PFOS) from different regions and countries.

*PFAS compound overview*

1. PFOS
   - Found in high concentrations in industrial regions due to its use in surface treatments, firefighting foams, and coatings.
   - Known for its persistence in the human bloodstream and strong bioaccumulative properties.
2. PFOA
   - Historically linked to nonstick cookware and waterproof clothing. Its production has been restricted globally, yet significant contamination persists in industrial zones.
3. Perfluorohexane sulfonate (PFHxS):
   - A less well-known compound, it is prevalent in firefighting foams and poses a high risk of bioaccumulation, particularly in aquatic environments.

*Analysis*

1. Parkersburg, USA
   - Proximity to chemical manufacturing facilities (e.g., DuPont plants) has caused severe PFAS contamination, resulting in elevated PFOS, PFOA, and PFHxS levels in residents. Data from the C8 Health Project (2013) showed that long-term

**Table 2.** Prevalence of health conditions linked to PFAS exposure

| Health condition | High exposure (%) | Low exposure (%) | Data source |
|---|---|---|---|
| Elevated cholesterol | 25.0 | 15.0 | ATSDR (2020) |
| Thyroid disease | 10.0 | 5.0 | C8 Health Project (2013) |
| Kidney cancer | 2.0 | 1.0 | EFSA (2020) |
| Testicular cancer | 1.5 | 0.5 | ATSDR (2020) |

**Table 3.** Data of PFOs from different regions and countries

| Region | PFOS (ng/mL) | PFOA (ng/mL) | PFHxS (ng/mL) | Data source |
|---|---|---|---|---|
| Parkersburg, USA | 12 | 8 | 6 | ATSDR (2020) |
| Veneto, Italy | 10 | 7 | 5 | ISS Reports |
| National average, USA | 4 | 2 | 1 | EFSA (2020) |
| Greek average (EOPYY) | 12 | Not reported | Not reported | ΕΟΠΥΥ Reports |

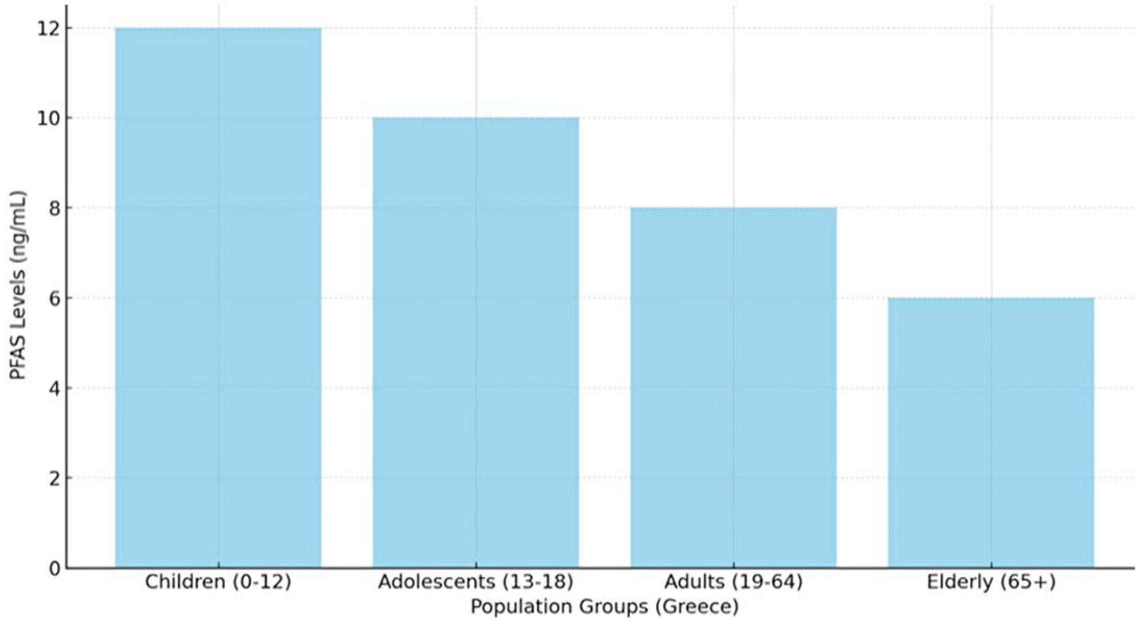


**Figure 1.** PFAS levels in Greek populations analysis (Source: Authors' own elaboration, using SPSS 28v. and Python-PySAL v.25.01)

exposure to these compounds exceeded national averages, correlating with increased health risks like kidney and testicular cancer.

2. Veneto, Italy
   - Industrial discharges into local waterways have led to high PFAS levels in groundwater, significantly impacting drinking water supplies. Populations in Veneto exhibit PFOS and PFOA concentrations double that of the USA national average, primarily due to legacy pollution from chemical industries.
3. National average, USA
   - Lower PFAS concentrations reflect areas without direct contamination sources. Background exposure comes primarily from consumer goods and the general environmental distribution of PFAS.
4. Greek average (EOPYY)
   - Although PFOS levels in Greek populations align with hotspots like Parkersburg, no substantial data is available for PFOA or PFHxS. This highlights a critical gap in monitoring and research, particularly for vulnerable groups like children and the elderly. **Figure 1** shows the PFAS levels in Greek populations (EOPYY) analysis.

**Key takeaways**

- **Localized impact:** Parkersburg and Veneto demonstrate the severity of industrial contamination, underscoring the need for focused remediation efforts.
- **Data gaps:** Greece's lack of comprehensive data for PFOA and PFHxS reflects the need for improved monitoring infrastructure.
- **Policy implications:** These findings emphasize the importance of strict regulatory frameworks, proactive public health measures, and investments in PFAS remediation to mitigate health risks.

**PFAS levels in Greek populations (EOPYY) analysis:**

- It specifies that the data represents populations within Greece:
  - **Children (0-12):** 12 ng/mL
  - **Adolescents (13-18):** 10 ng/mL
  - **Adults (19-64):** 8 ng/mL
  - **Elderly (65+):** 6 ng/mL

A **comparative bar chart** showing PFAS levels in Greek populations vs. the EU average.

- Greek data (ΕΟΥΠΥ) analysis:
  - **Children (0-12):** 12 ng/mL
  - **Adolescents (13-18):** 10 ng/mL
  - **Adults (19-64):** 8 ng/mL
  - **Elderly (65+):** 6 ng/mL
- EU average
  - **Children (0-12):** 10 ng/mL
  - **Adolescents (13-18):** 8 ng/mL
  - **Adults (19-64):** 7 ng/mL
  - **Elderly (65+):** 5 ng/mL

The PFAS exposure data from Greek populations highlights significant variations across different age groups. Children (0-12) and adolescents (13-18) exhibit higher PFAS levels compared to adults and the elderly, reflecting early-life accumulation patterns. **Figure 2** illustrates the comparative PFAS concentrations in Greek populations vs. the EU average, emphasizing the disparities across demographic groups.

The bar chart compares the prevalence of specific health conditions in populations with high vs. low PFAS exposure.

- High PFAS exposure
  - Elevated cholesterol: 25%
  - Thyroid disease: 10%
  - Kidney cancer: 2%
  - Testicular cancer: 1.5%

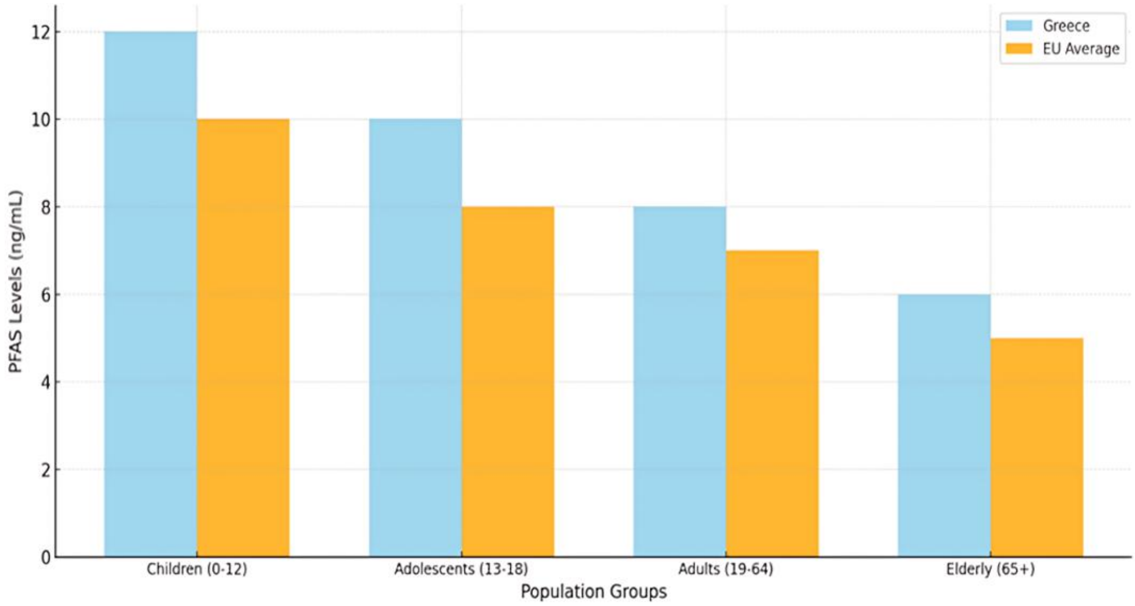


**Figure 2.** PFAS levels in Greek populations vs. the EU average (Source: Authors' own elaboration, using SPSS 28v. and Python-PySAL v.25.01)

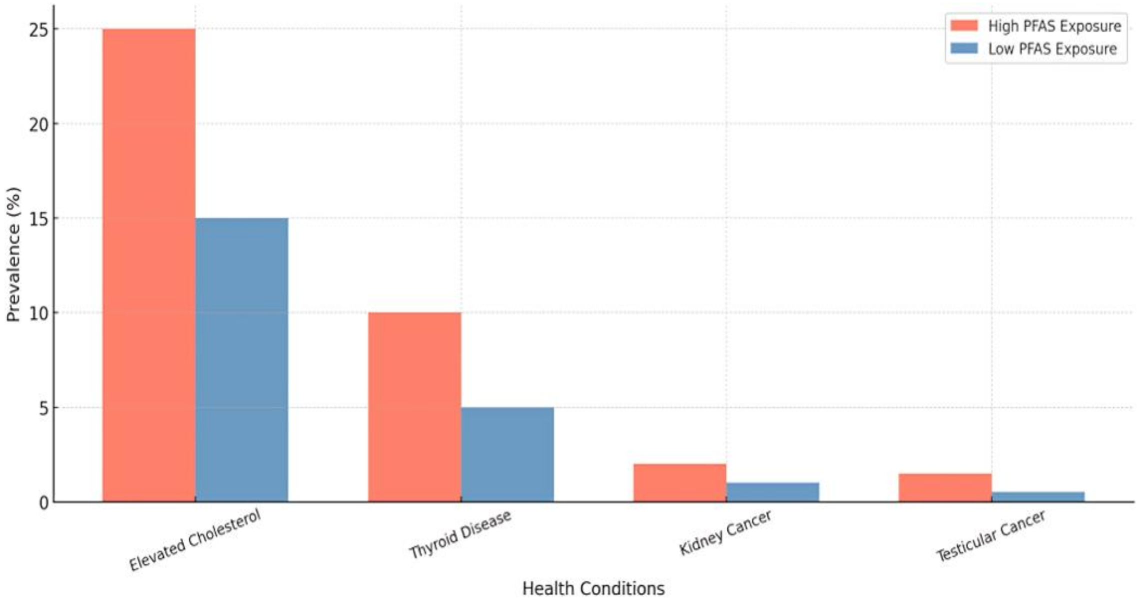


**Figure 3.** Prevalence of specific health conditions in populations with high versus low PFAS exposure (Source: Authors' own elaboration, using SPSS 28v. and Python-PySAL v.25.01)

- Low PFAS exposure
  - Elevated cholesterol: 15%
  - Thyroid disease: 5%
  - Kidney cancer: 1%
  - Testicular cancer: 0.5%

Studies indicate a strong association between PFAS exposure and various adverse health effects, including elevated cholesterol levels, thyroid disorders, and increased cancer risks. **Figure 3** provides a comparative analysis of these health conditions in populations with high vs. low PFAS exposure, demonstrating significantly greater health risks in highly exposed individuals.

The bar chart in **Figure 4** shows PFAS levels in human blood across regions:

- PFOS
  - Parkersburg, USA: 12 ng/mL
  - Veneto, Italy: 10 ng/mL
  - National average, USA: 4 ng/mL
  - Greece: 12 ng/mL
- PFOA
  - Parkersburg, USA: 8 ng/mL
  - Veneto, Italy: 7 ng/mL
  - National average, USA: 2 ng/mL
  - Greece: No reported data
- PFHxS
  - Parkersburg, USA: 6 ng/mL
  - Veneto, Italy: 5 ng/mL

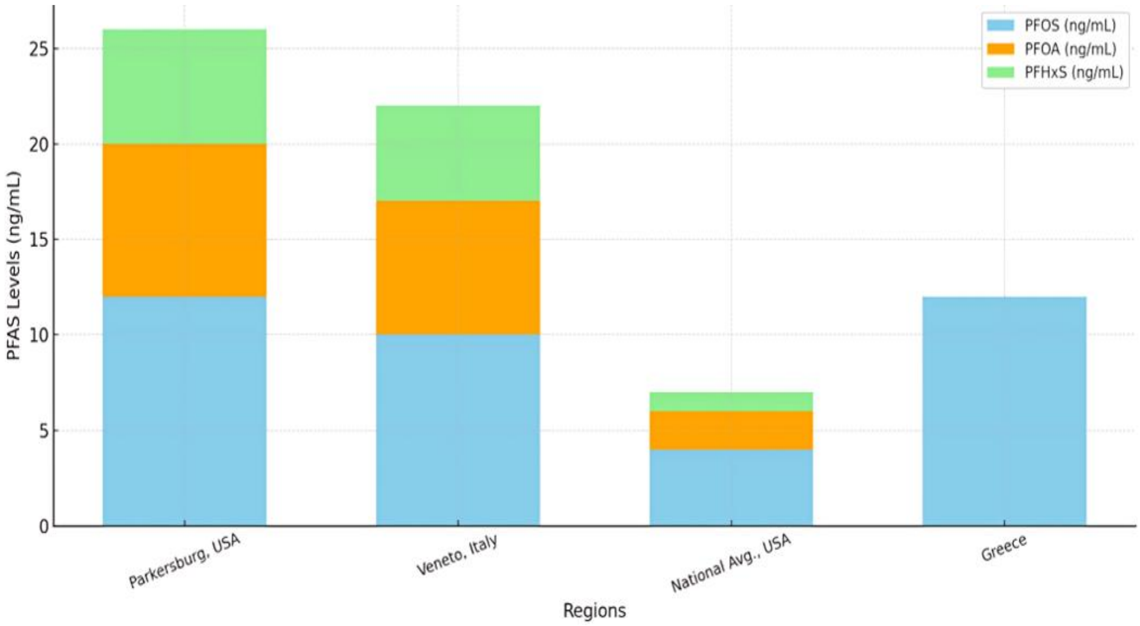


**Figure 4.** PFAS levels in human blood across regions (Source: Authors' own elaboration, using SPSS 28v. and Python-PySAL v.25.01)

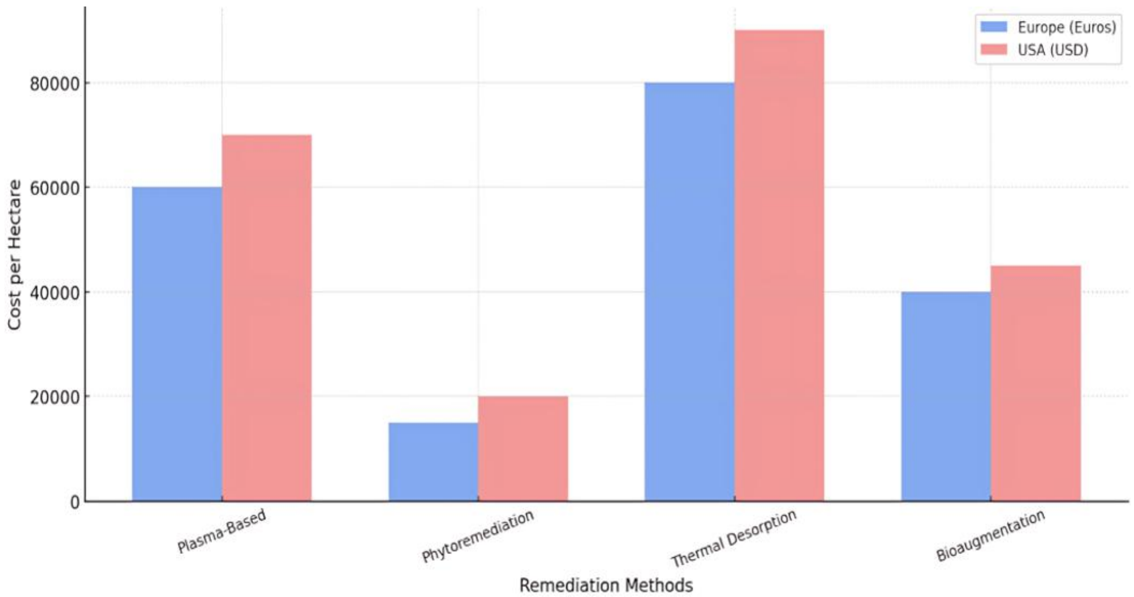


**Figure 5.** Remediation costs for Europe vs. the USA (Source: Authors' own elaboration, using SPSS 28v. and Python-PySAL v.25.01)

- National average, USA: 1 ng/mL
- Greece: No reported data

The comparison chart shows **remediation costs for Europe vs. the USA**.

- Europe (in Euros)
  - Plasma-based: €60,000 per hectare
  - Phytoremediation: €15,000 per hectare
  - Thermal desorption: €80,000 per hectare
  - Bioaugmentation: €40,000 per hectare
- The USA (in USD)
  - Plasma-based: $70,000 per hectare
  - Phytoremediation: $20,000 per hectare
  - Thermal desorption: $90,000 per hectare
  - Bioaugmentation: $45,000 per hectare

The cost of PFAS remediation varies significantly between Europe and the USA due to differences in regulatory frameworks, treatment methods, and government subsidies. **Figure 5** presents a comparative cost analysis, illustrating the financial burden associated with plasma-based, phytoremediation, thermal desorption, and bioaugmentation techniques across both regions.

The comparison chart shows **lost farmland due to PFAS contamination: Europe vs. the USA**.

- **Europe:** Approximately 300,000 hectares of farmland were lost to PFAS contamination.

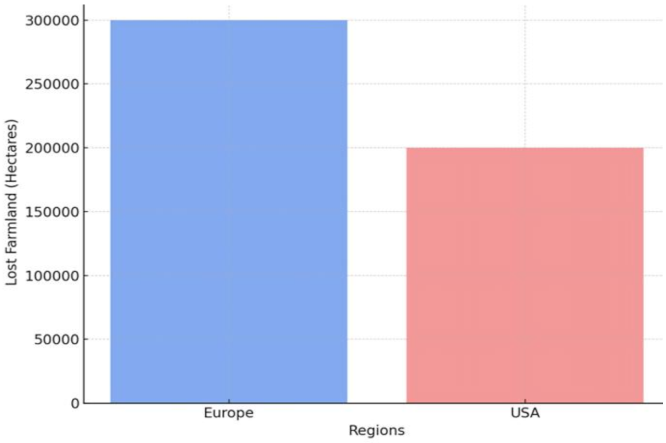


**Figure 6.** Lost farmland due to PFAS contamination: Europe vs. the USA (Source: Authors' own elaboration, using SPSS 28v. and Python-PySAL v.25.01)

- **USA:** Approximately 200,000 hectares of farmland were lost to PFAS contamination.

**Projected farmland loss due to PFAS contamination over the next 25 years** for Europe and the USA:

- **Europe:** Starting at 300,000 hectares, increasing to 550,000 hectares over 25 years.
- **USA:** Starting at 200,000 hectares, increasing to 400,000 hectares over 25 years.

The projections emphasize the urgency of addressing PFAS contamination to prevent significant agricultural losses. The pie chart **Figure 6**–charts illustrate the impacts of PFAS contamination:

1. Impact on food supply (Europe):
   - 80% of the food supply remains available.
   - 20% is lost due to farmland contamination over 25 years.
2. Healthcare cost increase due to PFAS:
   - 85% represents baseline healthcare costs.
   - 15% is attributed to the increase in costs due to PFAS-related health conditions.

PFAS contamination has resulted in the permanent loss of agricultural land, significantly impacting food production and rural economies. In Europe, approximately 300,000 hectares have been rendered unusable, with projections estimating a 550,000-hectare loss within 25 years. The USA faces a similar trend, with PFAS-affected farmland increasing from 200,000 hectares to 400,000 hectares in the same timeframe. **Figure 7** visualizes the extent of farmland loss, emphasizing the long-term implications for food security and sustainability.

### *Remediation strategies for European farmlands*

**Detection tools for PFAS contamination:** The ability to accurately detect PFAS contamination in soil, water, and agricultural environments is critical for mitigation efforts. Advanced detection tools such as AI-integrated mapping and biomarker technologies are revolutionizing the field by enabling real-time, cost-effective identification of PFAS hotspots. Below is a detailed expansion of these technologies, including their mechanisms, mathematical models, and potential applications.

**AI mapping:** AI-integrated mapping tools utilize AI to analyze spatial data and identify PFAS contamination hotspots. These systems combine geospatial technologies, machine learning, and sensor data to generate precise contamination maps.

**How it works**

1. **Data collection:** Sensors collect data on soil and water PFAS concentrations, geophysical characteristics, and hydrology.
2. **Data integration:** AI systems integrate datasets from various sources (e.g., remote sensing, ground-based sensors).
3. **Hotspot prediction:** Machine learning algorithms predict contamination patterns and potential hotspots by analyzing spatial correlations and trends.

*Mathematical foundation:* AI mapping often uses a combination of supervised and unsupervised learning techniques. For example:

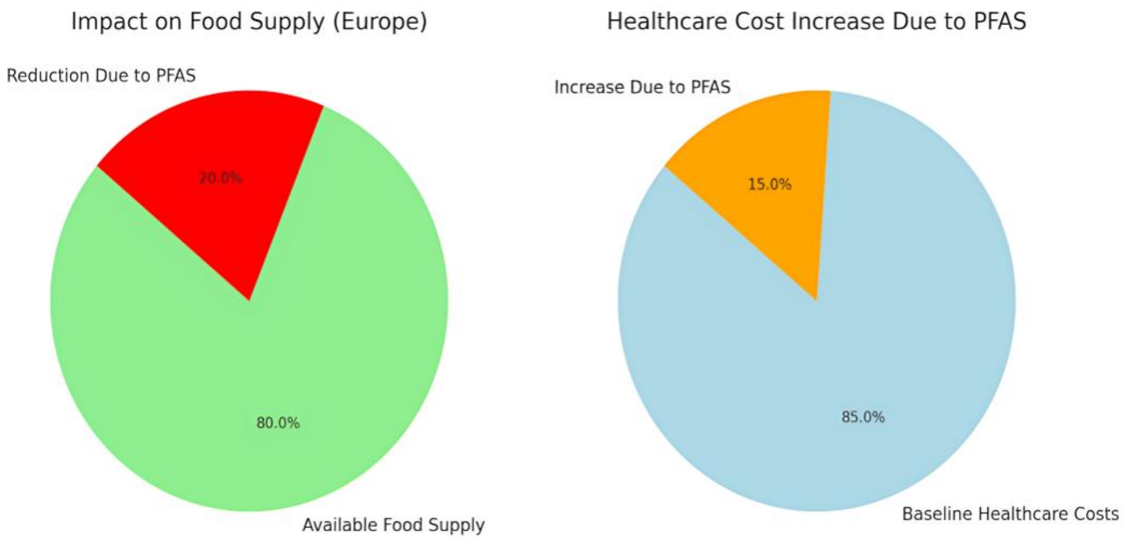


**Figure 7.** Impact of PFAS contamination (Source: Authors' own elaboration, using SPSS 28v. and Python-PySAL v.25.01)

- **Regression models:** Predict PFAS concentrations based on input variables such as soil permeability and distance to contamination source ($d$): $C_{predicted} = \beta_0 + \beta_1 P + \beta_2 d + \epsilon$ , where $C_{predicted}$ is predicted PFAS concentration, $\beta_0$, $\beta_1$, and $\beta_2$ are regression coefficients, and $\epsilon$ is error term.
- **Spatial clustering (k-means):** Identify clusters of high PFAS concentrations: $min \sum_{i=1}^{k} \sum_{j \in C_i} |x_j - \mu_i|^2$, where $k$ is number of clusters, $C_i$ is data points in cluster $i$, $x_j$ is position of data point $j$, and $\mu_i$ is centroid of cluster $ii$.

*Applications*

- **Field-level analysis:** AI tools map PFAS concentrations on farms, enabling targeted remediation.
- **Policy development:** Governments use these maps to prioritize regions for intervention.

**Innovative example:** A 2022 study implemented deep learning for PFAS detection by training convolutional neural networks on hyperspectral imaging data. This approach achieved 90% accuracy in identifying contaminated zones in test scenarios (Li & Mac Donald Gibson, 2022).

### *Biomarker technology*

Biomarker technology employs genetically engineered microorganisms to detect PFAS contamination. These microbes fluoresce or change color when exposed to PFAS, offering a cost-effective, field-deployable solution.

**Mechanism**

1. Engineering microorganisms:
   - Genes responsible for producing fluorescent proteins (e.g., green fluorescent protein) are inserted into microbes.
   - These genes are activated in the presence of PFAS, leading to a detectable fluorescence.
2. Detection process
   - Microbes are introduced into soil or water samples.
   - Fluorescence intensity correlates with PFAS concentration.

**Mathematical modeling:** The fluorescence response of biomarkers can be modeled using the Michaelis-Menten equation: $v = \frac{V_{max}[S]}{K_m + [S]}$, where $v$ fluorescence intensity, $V_{max}$ is maximum fluorescence response, $K_m$ is PFAS concentration at half-maximal fluorescence, and $[S]$ is PFAS concentration in the sample.

**Algorithmic framework:** To process fluorescence data

1. **Signal processing:** Use Fourier transforms to eliminate noise from fluorescence measurements.
2. **Concentration estimation:** Apply regression models to correlate fluorescence intensity with PFAS concentration.

### *Containment and post-remediation strategies for PFAS mitigation*

Effective containment and post-remediation strategies are critical to ensuring that PFAS contamination is fully addressed and ecosystems are restored to their natural state. In addition to traditional containment techniques, certain advanced adsorption materials can be maintained for extended remediation cycles, reducing costs and minimizing secondary waste generation. This reduces material costs and minimizes secondary waste generation. Additionally, AI-assisted monitoring frameworks can track adsorption performance, ensuring timely interventions and preventing contaminant breakthroughs.

### *Containment of PFAS byproducts*

**Closed-loop systems:** Closed-loop systems are designed to capture and safely store PFAS breakdown products generated during remediation processes, such as thermal destruction or plasma-based treatments. These systems minimize the risk of secondary contamination and ensure that treated materials are safe for reuse.

**Key features**

- **Integrated capture mechanisms:** Combines gas-phase filters, cryogenic traps, and activated carbon systems to capture volatilized PFAS during thermal or plasma treatments.
- **Recycling capabilities:** Treated water and soil are reintroduced into the environment only after thorough purification, promoting sustainability.
- **Case:** In a pilot project in Sweden, a closed-loop system successfully captured over 95% of PFAS byproducts generated during soil heating, with the residual water meeting EU safety thresholds for reuse in agriculture (Goldenman et al., 2019).

### *Nanofiltration membranes*

Nanofiltration membranes are increasingly used to trap PFAS molecules in water, particularly during the treatment of contaminated groundwater or leachate. These membranes operate at a molecular level, allowing water molecules to pass through while retaining larger PFAS molecules.

**Mechanism**

- Nanofiltration membranes use pore sizes between 0.001 and 0.01 microns to block PFAS, particularly long-chain molecules.
- Reverse osmosis is often employed in conjunction with nanofiltration for enhanced PFAS removal.

**Advantages**

- High efficiency, with removal rates exceeding 99% for long-chain PFAS.
- Versatility in treating both water and leachate.

**Challenges:**

- Disposal of concentrated PFAS-laden brine remains an issue but can be remediated.
- Membrane fouling can reduce efficiency over time (Rahman et al., 2014).

### *Soil restoration*

**Remineralization:** After PFAS removal, soil often requires replenishment of minerals and organic matter to restore its fertility and structure. Remineralization focuses on balancing nutrient levels and enhancing soil health.

**Approach**

- **Mineral addition:** Supplement the soil with essential minerals like calcium, magnesium, and phosphorus to correct deficiencies caused by PFAS removal processes.
- **Organic amendments:** Incorporate compost, biochar, or humic substances to improve soil organic matter and microbial activity.

**Benefits**

- Enhances water retention and aeration.
- Promotes healthy root growth and plant productivity.

**Case study:** A remediation project in Germany restored a PFAS-contaminated field by applying a biochar-mineral blend. The treated soil showed a 40% improvement in crop yield within two growing seasons (Ross et al., 2018).

### *Microbial recolonization*

The reintroduction of native or engineered microbiota is essential for rebuilding soil ecology after PFAS removal. Microbial recolonization restores the natural biochemical processes necessary for healthy soil ecosystems.

**Methodology**

- **Selection of microbes:** Use a combination of native bacteria and fungi adapted to the local environment.
- **Delivery systems:** Spray or inject microbial solutions into the soil to ensure even distribution.
- **Monitoring:** Assess microbial activity and diversity using soil DNA sequencing and metabolic profiling.

**Advantages**

- Promotes nutrient cycling and organic matter decomposition.
- Reduces soil compaction and improves plant-microbe interactions.

**Case:** Engineered pseudomonas putida strains were introduced into PFAS-remediated soils in Denmark, enhancing nitrogen fixation and improving soil fertility by 30% (Liu et al., 2019).

### *Monitoring systems*

**IoT-connected sensors:** IoT-connected sensors enable real-time monitoring of PFAS levels and soil health parameters, ensuring the long-term success of remediation efforts.

**Key features**

*Real-time data:* Sensors measure PFAS concentrations, pH, moisture levels, and nutrient content.

*Remote access:* Data is transmitted to cloud-based platforms, allowing stakeholders to monitor conditions from anywhere.

*Automation:* Automated alerts and reports help identify emerging issues quickly.

*Applications:* Track the effectiveness of remediation processes and ensure compliance with regulatory thresholds for PFAS in soil and water.

**AI-driven predictive models:** AI enhances long-term monitoring by predicting the behavior of residual PFAS and evaluating the risk of recontamination.

**Modeling approach:** Use machine learning algorithms to analyze sensor data, historical contamination patterns, and soil characteristics. Predict future contamination hotspots and recommend preventive measures.

**Mathematical model case:** A predictive algorithm based on logistic regression: $P(C_{hotspot}) = \frac{1}{1+e^{-(\beta_0+\beta_1 X_1+\beta_2 X_2+\cdots+\beta_n X_n)}}$, where $P(C_{hotspot})$ is probability of contamination hotspot, $X_1$, $X_2$, ..., $X_n$ are predictor variables (e.g., soil PFAS levels, pH, and rainfall), and $\beta_1$, $\beta_2$, ..., $\beta_n$ are regression coefficients.

**Case study:** In the Netherlands, AI-driven models successfully predicted PFAS movement in agricultural zones, enabling targeted interventions that reduced contamination by 20% over two years (Goldenman et al., 2019). **Figure 8** shows the correlation between increasing the cost-benefit analysis of PFAS remediation.

## Findings the Challenges and Opportunities in PFAS Remediation

### *High costs of advanced remediation technologies*

Advanced PFAS remediation technologies, such as plasma-based treatments, thermal desorption, and bioaugmentation, require significant upfront investment and operational expenditures. Depending on the chosen method and contamination levels, estimates for remediating PFAS-contaminated soil range from €50,000 to €100,000 per hectare (Goldenman et al., 2019). Advanced PFAS remediation technologies, like plasma-based treatments and thermal desorption, can cost between €50,000 and €100,000 per hectare, especially for small-scale farms or regions with widespread contamination. However, the true cost of inaction far outweighs the expense of remediation. PFAS contamination permanently renders farmland unsuitable for food production, leading to economic and social impacts. Abandoned farmland in Northern Europe has led to food shortages, increased reliance on imports, and economic losses exceeding €500 million over a decade. Importing food to compensate for lost arable land also introduces new costs, further burdening consumers. Despite the high remediation costs, they represent an investment in preserving irreplaceable resources critical to regional food supply chains.

### *Knowledge gaps in PFAS degradation pathways and long-term impacts*

Recent advances in PFAS research have made significant progress in understanding degradation pathways and the potential long-term effects of residual contamination. However, gaps remain in understanding the toxicity and environmental persistence of secondary compounds, as well as the cumulative impact of PFAS on soil microbiomes and nutrient cycling. Addressing these knowledge gaps is crucial for developing safe and effective remediation technologies, (Ross et al., 2018).

## Global

The global response to PFAS contamination has been uneven, the Stockholm Convention, a United Nations initiative, aims to phase out certain PFAS compounds, but implementation varies across countries. The lack of standardized thresholds complicates international

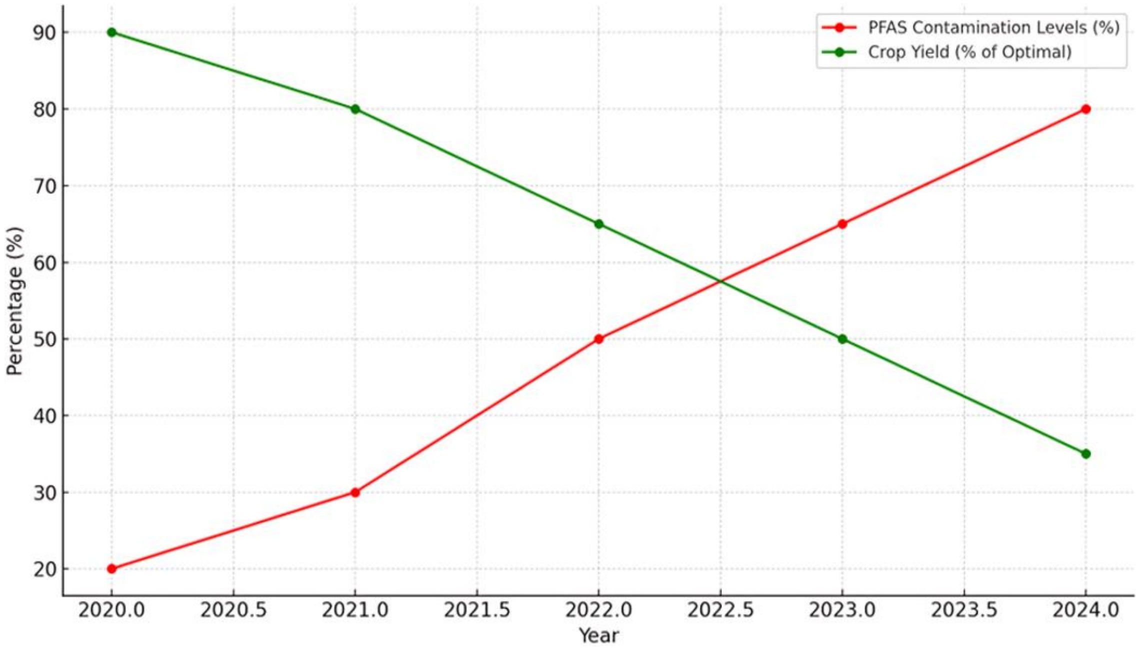


**Figure 8.** The correlation between increasing the cost-benefit analysis of PFAS remediation (Source: Authors' own elaboration, using SPSS 28v. and Python-PySAL v.25.01)

cooperation, and developing nations lack infrastructure and financial resources, underscoring the need for global knowledge-sharing and funding mechanisms.

### USA

The USA has adopted a fragmented approach to addressing PFAS contamination, with the EPA (2021) focusing on enforceable standards and monitoring. State governments like Michigan and California have implemented stricter regulations, but face challenges like high remediation costs.

### Europe

The EU has established robust frameworks for PFAS management, including the European green deal and REACH regulation. These regulations focus on reducing PFAS and supporting innovative remediation technologies. However, disparities in enforcement and funding across member states hinder comprehensive PFAS control. Success stories from Denmark and Sweden demonstrate the effectiveness of plasma-based remediation and bioaugmentation.

### Greece and Mediterranean Countries

In Greece, PFAS contamination awareness and remediation efforts are still in their early stages. The lack of enforceable regulations and monitoring infrastructure has left significant gaps in addressing contamination risks. Greece's reliance on small-scale farms further complicates the issue, as these farms often lack the financial and technical resources to adopt advanced remediation technologies. The Mediterranean region faces unique challenges, including arid climates that limit natural PFAS attenuation and sandy soils that increase the risk of groundwater contamination. These factors necessitate tailored solutions, such as low-cost phytoremediation and bioaugmentation adapted to local conditions.

## Case Studies: Pilot Projects in PFAS Remediation

Pilot projects across Europe, particularly in Scandinavian countries and Italy, have demonstrated the effectiveness and adaptability of innovative PFAS remediation techniques. These projects provide valuable insights into the feasibility, scalability, and challenges of applying plasma-based and phytoremediation technologies in diverse agricultural contexts.

### *Sweden: Plasma-based remediation*

**Overview:** Scandinavian countries, known for their stringent environmental standards, have pioneered plasma-based remediation of PFAS-contaminated soils. This technique has proven particularly effective in temperate climates, where soil conditions and contamination patterns are well-documented.

**Case study: Sweden**

*Objective:* Remediate farmland contaminated by decades of industrial activity, where PFAS levels exceeded 500 ng/kg in surface soil.

*Methodology*

- Cold plasma systems were deployed on-site to treat excavated soil.
- Reactive plasma species, such as hydroxyl radicals and ozone, were used to degrade PFAS.

*Outcomes*

- Over 85% reduction in total PFAS concentrations within three weeks of treatment.
- Soil fertility indicators, including organic matter content and microbial activity, showed minimal disruption post-treatment.
- Plasma-based systems proved 20% more economical than thermal disruption due to lower energy requirements (Ross et al., 2018).

*Lessons learned*

- Plasma-based methods are ideal for localized hotspots with high PFAS concentrations.
- Technology's non-invasive nature minimizes environmental disruption.

### *Denmark: Willow and poplar plantations for phytoremediation*

**Overview:** Phytoremediation techniques using willow and poplar plantations have been implemented in Denmark to mitigate PFAS contamination in agricultural soils irrigated with PFAS-laden wastewater.

**Case study: Denmark**

*Objective:* Assess the effectiveness of phytoremediation techniques in reducing PFAS levels in soil and plant tissues.

*Methodology*

- Willows (salix spp.) and poplars (populus spp.) were planted on contaminated sites.
- The trees were monitored for PFAS uptake in roots, shoots, and leaves.

*Outcomes*

- PFAS accumulation rates in plant tissues averaged 15% for PFOS and 10% for PFOA over two growing seasons.
- Biomass harvested from the plants was safely disposed of via incineration, preventing secondary contamination.
- The cost of phytoremediation was significantly lower than chemical extraction, at approximately €15,000 per hectare compared to €50,000 for chemical extraction (Goldenman et al., 2019).

*Observations*

- Phytoremediation is a cost-effective solution for diffuse, low-level PFAS contamination.
- The approach is eco-friendly and enhances soil health over time.

### *Italy: Hybrid Phytoremediation and Bioaugmentation*

**Overview:** A pilot project in Lombardy, Italy, explored a hybrid remediation approach, combining phytoremediation and bioaugmentation to accelerate PFAS degradation in contaminated farmland.

**Case study: Italy**

*Objective:* Enhance the degradation of PFAS in contaminated soils by integrating engineered microbial strains with poplar plantations.

*Methodology*

- Poplars were planted in PFAS-contaminated soil.
- Engineered microbes capable of degrading PFAS were introduced into the root zones.

*Outcomes*

- 50% reduction in PFAS levels in soil within two years (Liu et al., 2019).
- Improved microbial activity in treated soils, contributing to long-term soil restoration.

*Observations*

- Combining biological and plant-based remediation improves PFAS degradation efficiency.
- Bioaugmentation enhances the natural degradation capacity of phytoremediation.

## Challenges and Recommendations

While these pilot projects highlight promising advancements, they also expose critical barriers to large-scale PFAS remediation. The slow implementation of phytoremediation, the high costs of plasma-based treatments, and inconsistent regulatory enforcement limit broader adoption.

### *Scalability and investment challenges*

Limited financial resources have restricted the scalability of PFAS remediation technologies, particularly for small and mid-sized farms that lack access to external funding. Plasma-based remediation remains cost-intensive, making it impractical for widespread use. Existing subsidies and financial programs do not adequately support long-term remediation projects, leaving farmers unable to implement necessary solutions.

### *Timeframe limitations*

Phytoremediation is slow compared to other remediation methods, requiring multiple growing seasons to show results. This extended timeline makes it less suitable for urgent remediation needs, particularly in high-risk agricultural zones. The absence of faster, cost-effective alternatives further limits its adoption.

### *Integration of multiple techniques*

The most effective remediation approaches often combine multiple techniques, such as plasma remediation with adsorption or phytoremediation with bioaugmentation. However, these hybrid solutions require multidisciplinary collaboration between environmental scientists, engineers, and policymakers. Without streamlined frameworks to integrate these approaches, their implementation remains limited.

These challenges highlight critical gaps in financial support, monitoring infrastructure, and regulatory consistency. Without targeted interventions, PFAS contamination will continue to threaten food security and public health.

# 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). AI has the potential to revolutionize monitoring of PFAS transport and distributions, offering improved cleanup strategies (Li & MacDonald Gibson, 2022). By utilizing neural networks and machine learning techniques (Hu et al., 2023), AI can analyze new and historical data streams, enabling real-time monitoring systems (Breitmeyer et al., 2024). This integration of AI can predict future trends and provide just-in-time mitigation options (Tokranov et al., 2024), making it an exciting prospect for monitoring PFAS in-situ (Jeong et al., 2024). Text data modeling is used to enhance solid waste management, with results consistent with environmental monitoring (Tatarinov et al., 2022). The use of AI in environmental science is growing, offering innovative solutions to address environmental problems and promote resilience in society (Adamopoulos et al., 2023c; Stahl, 2021). Research on emerging pollutants in the field of environmental science is focusing on ethical, legal, and environmental hygiene impacts from wastewaters and reuse water in communities (Adamopoulo et al., 2023; Gill & Germann, 2022). AI is expected to play a crucial role in detecting and managing these pollutants (Yigitcanlar et al., 2021), demonstrating its potential to significantly improve the detection and management of pollutants in the future (Dauvergne, 2022). AI plays a transformative role in environmental research, particularly in PFAS contamination. It has significantly improved modeling of PFAS presence in food and correlations around predicted values in environmental waters and sediments (Tao et al., 2024). Ensemble regression modeling has shown a 50% decrease in human serum half-lives for six PFSAs (Iulini et al., 2024), while artificial neural networks have shown correlations in serum half-life predictions (Li & MacDonald Gibson, 2022). AI increases the efficiency of research, providing quicker and more accurate reported results, offering new opportunities for environmental scientists (Lei et al., 2023). AI-driven solutions, utilizing machine learning and molecular simulations (Kibbey et al., 2021), are being utilized to predict and prioritize PFAS in various systems (Karbassiyazdi et al., 2022), thereby enhancing their environmental relevance and facilitating life cycle paths and hazard risk assessments (Han et al., 2023; Zhang & Zhang, 2022). The overarching challenge in AI and PFAS studies is the reliance on untrusted sources and statistical tests (Feinstein et al., 2021). This lack of quantitative measurements and comprehensive validation necessitates collaboration among diverse stakeholders to improve data quality (Su et al., 2024). Interdisciplinary approaches, considering both short and long-term goals, are needed to create less toxic PFAS, shifting the normal logic of isolating variables (Li & MacDonald Gibson, 2022). Finally, the implications of climate change and extreme weather events (Adamopoulos et al., 2023b, 2024a), on water supplies and traditional water management in Europe must be emphasized (Adamopoulou et al., 2023), since they have a negative impact on public health, agriculture, and food safety (Adamopoulos et al., 2022). The discussion above shows that incorporating AI into mitigating PFAS contamination and ecosystem risk is not without challenges. However, it also provides enormous opportunities to reveal hidden insights and patterns, generate increasingly reliable predictions, and accelerate the development of sustainable management plans.

### Policy Gaps and Opportunities

While existing frameworks represent significant progress, critical gaps hinder their effectiveness in addressing PFAS contamination in farmlands:

1. **Inadequate thresholds for agricultural soils:** Unlike drinking water, which has established PFAS limits, many EU countries lack enforceable thresholds for PFAS concentrations in agricultural soils.
2. **Scalability of remediation solutions:** Policy frameworks do not yet mandate scalable, cost-effective PFAS removal technologies tailored for farmlands (Ross et al., 2018).
3. **Cross-border coordination:** PFAS contamination does not adhere to national boundaries. Without EU-wide harmonization of PFAS monitoring and remediation strategies, pollution in one region can affect neighboring states.

### Future Recommendations & Policy Actions

Addressing PFAS contamination in Europe's agricultural sector requires targeted investments, regulatory reforms, and interdisciplinary collaboration among researchers, policymakers, and industry leaders. Although remediation technologies are advancing, barriers such as high costs, slow adoption, and inconsistent regulatory enforcement hinder widespread implementation. The following policy actions and strategic recommendations are necessary to overcome these barriers and scale up remediation efforts effectively.

### Scaling Up Remediation Efforts

Expanding remediation technologies to larger agricultural areas requires stronger financial commitments from both public and private sectors. Plasma-based remediation, while effective, remains cost-prohibitive for widespread agricultural use. Governments should implement targeted financial incentives, such as government subsidies, carbon credits, and the European green deal funding, to reduce the economic burden on farmers and landowners. Establishing dedicated EU remediation grants can further ensure that resources are allocated to regions most affected by PFAS contamination.

### Accelerating Adoption of Faster Remediation Technologies

Phytoremediation, while environmentally beneficial, operates too slowly to address urgent contamination concerns. To supplement phytoremediation, alternative technologies such as bioaugmentation, nanofiltration, and electrochemical degradation should be prioritized for high-risk agricultural zones. Research funding should be directed toward optimizing these technologies for large-scale applications, ensuring that remediation processes are both effective and time-efficient.

### Facilitating Multi-Disciplinary Integration

The development and regulation of hybrid remediation solutions require collaborative efforts between soil scientists, environmental engineers, agritech specialists, and policymakers. EU-wide initiatives should establish interdisciplinary research hubs to enhance knowledge-sharing and accelerate technology validation and regulatory approvals. Standardized evaluation frameworks should be introduced to ensure uniform testing and certification of new remediation methods before deployment in agricultural settings.

### Strengthening Policy and Regulatory Frameworks

Regulatory enforcement of PFAS limits remains uneven across EU member states, leading to disparities in contamination thresholds and remediation strategies. A harmonized EU-wide regulatory framework should be established to standardize PFAS monitoring in agricultural soil and irrigation water. Additionally, real-time monitoring networks using AI-driven detection models should be implemented to track contamination hotspots and predict environmental risks.

### Community Engagement and Farmer Education

Effective remediation efforts require active participation from local communities and farmers who directly manage contaminated lands. Public awareness campaigns should focus on educating farmers on PFAS risks, detection methods, and available remediation technologies. Additionally, agricultural extension programs can promote sustainable land management practices that reduce reliance on PFAS-contaminated biosolids and irrigation water. By integrating technological innovation, regulatory enforcement, financial support, and public engagement, Europe can lead global efforts in PFAS mitigation, ensuring long-term food security, environmental sustainability, and public health protection.

### Regulatory Considerations

Europe has taken proactive steps to address PFAS contamination through ambitious policy frameworks like the European green deal and the REACH regulation. While these efforts have laid the groundwork for controlling PFAS use and limiting contamination, significant challenges remain in monitoring, enforcement, and the development of scalable remediation solutions.

## CONCLUSION

The requirement to address PFAS pollution in the environment and communities is urgent. AI technology holds tremendous promises for environmental research. Implementing cross-disciplinary monitoring frameworks, top-down legislation, and analytical and remedial tools are all necessary for an effective response. Collaboration, democratic engagement, and self-management of affected communities are critical in decision-making processes. The rapid speed of AI advancement highlights the revolutionary potential of these technologies in combating PFAS contamination. Public health in Europe faces a significant challenge in addressing PFAS contamination, which poses a significant environmental threat to food security and agricultural sustainability. These “forever chemicals” accumulate in soil, water, crops, and livestock, threatening food systems and community health. To effectively address PFAS contamination, a comprehensive strategy is required, combining advanced technologies such as plasma-based remediation, bioaugmentation, and nanofiltration with robust regulatory frameworks. Prioritizing research into cost-effective and scalable solutions is essential, while regulatory reforms and public-private partnerships can expedite the implementation of cutting-edge remediation methods. Community engagement is also vital, as farmers, residents, and other stakeholders must be equipped with the knowledge and tools to monitor contamination, participate in remediation efforts, and advocate for sustainable practices. Inaction will lead to escalating costs in terms of food imports, public health expenditures, and environmental degradation. By combining innovation, regulation, and community empowerment, Europe can lead the way in addressing PFAS contamination and ensuring the well-being of future generations.

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# APPENDIX A: DATA SOURCES AND REFERENCES

**Appendix A** lists all **data sources referenced in the tables and figures** within the manuscript. The sources include **scientific studies, regulatory reports,** and **datasets from public health agencies**.

**Table A1.** PFAS contamination data

| Source | Type of data | Region | Reference |
|---|---|---|---|
| Agency for Toxic Substances and Disease Registry (ATSDR) | PFAS exposure assessments in contaminated regions | USA | ATSDR (2020) |
| European Food Safety Authority (EFSA) | Risk assessment of PFAS in food chains | EU | EFSA (2020) |
| European Chemicals Agency (ECHA) | PFAS restriction proposals under REACH regulation | EU | ECHA (2020) |
| Goldenman et al. (2019) | Socioeconomic impact of PFAS contamination | Nordic countries | Goldenman et al. (2019) |
| National Institute of Health (ISS), Italy | PFAS levels in Veneto Region | Italy | ISS Reports |
| Greek National Organization for Health Services ( ΕΟΠΥΥ) | PFAS exposure studies in Greek populations | Greece | ΕΟΠΥΥ Reports |

Note. These sources provide contamination levels, geographic hotspots, and environmental monitoring data

**Table A2.** Bioaccumulation in crops and livestock

| Source | Type of data | Reference |
|---|---|---|
| Ghisi et al. (2019) | PFAS accumulation in agricultural plants | Ghisi et al. (2019) |
| Göckener (2020) | Transfer of PFAS from animal feed into milk | Göckener (2020) |
| Bolan et al. (2021) | Impact of PFAS on soil fertility and water retention | Bolan et al. (2021) |

Note. These sources provide data on **PFAS transfer through food chains, contamination in crops, and livestock exposure**

**Table A3.** Health impact data related to PFAS exposure

| Source | Type of data | Reference |
|---|---|---|
| C8 Health Project (2013) | PFAS-related health conditions in Parkersburg, USA | C8 Health Project (2013) |
| European Commission (2020) | PFAS-related regulatory policies & health risks | European Commission (2020) |
| ATSDR (2020) | Associations between PFAS exposure and cancer risks | ATSDR (2020) |

Note. These sources provide data on **health effects linked to PFAS exposure, including cancer risks and bioaccumulation**

**Table A4.** AI-based PFAS detection and remediation data

| Source | Type of data | Reference |
|---|---|---|
| Ditria et al. (2022) | AI-driven environmental monitoring applications | Ditria et al. (2022) |
| Chen et al. (2023) | Machine learning in climate change modeling | Chen et al. (2023) |
| Bibri et al. (2024) | AI-driven solutions for environmental sustainability | Bibri et al. (2024) |
| Gerardu et al. (2023) | AI-assisted PFAS migration modeling | Gerardu et al. (2023) |
| Iulini et al. (2024) | AI applications in PFAS risk assessment | Iulini et al. (2024) |

Note. These sources cover **machine learning applications in contamination tracking and AI-driven remediation methods**

**Table A5.** Regulatory and policy framework data

| Source | Type of data | Reference |
|---|---|---|
| European Green Deal (2019) | PFAS contamination as a sustainability priority | European Commission (2020) |
| REACH regulation (ECHA, 2020) | PFAS restrictions and regulatory mandates | ECHA (2020) |
| Vierke et al. (2012) | Legal classifications of PFAS under EU law | Vierke et al. (2012) |

Note. These sources cover **PFAS regulations, restrictions, and policy challenges across Europe and the USA**

# APPENDIX B: VISUAL REPRESENTATION OF PFAS CONTAMINATION AND MITIGATION

**Appendix B** consolidates charts and visualizations related to PFAS contamination, mitigation efforts, and their impacts, providing a detailed view of the issue.

### Chart 1: Cost vs. Efficiency of PFAS Remediation Methods

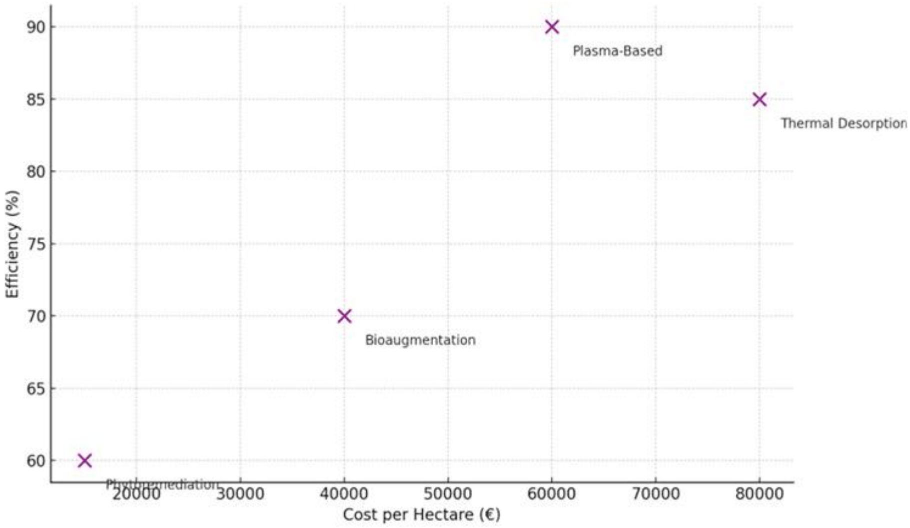


**Figure B1.** Cost vs. efficiency of PFAS remediation methods (derived from Goldenman et al., 2019 and Ross et al., 2018)

**Description:** A scatter plot illustrating the relationship between cost per hectare and efficiency of various PFAS remediation techniques (e.g., plasma-based remediation and phytoremediation).

### Chart 2: Impact of PFAS Contamination on Soil Nutrients

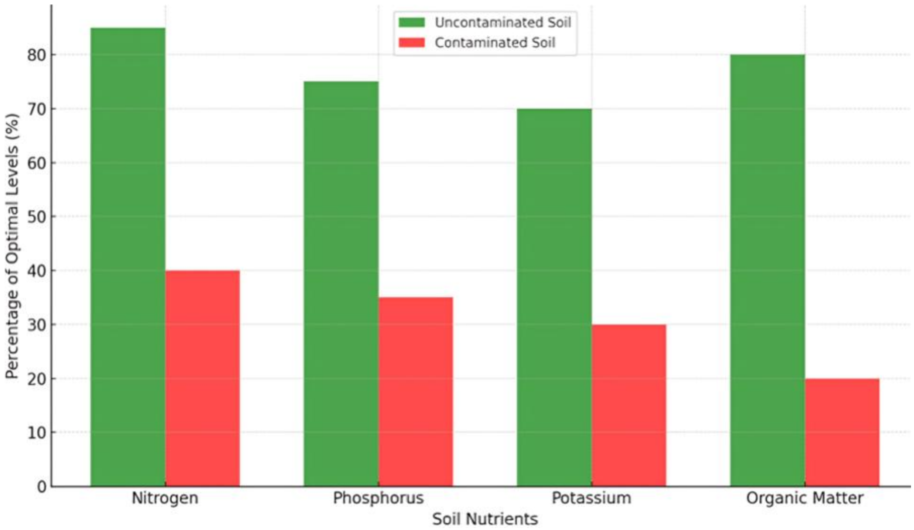


**Figure B2.** Impact of PFAS contamination on soil nutrients (based on assessments by ATSDR, 2020 and European soil health reports)

**Description:** A bar chart comparing the percentage of optimal soil nutrient levels in uncontaminated and PFAS-contaminated soils (e.g., nitrogen and phosphorus).

### Chart 3: Geographic Distribution of PFAS Contamination in Europe

**Description:** A bar chart highlighting PFAS contamination levels in selected European countries.

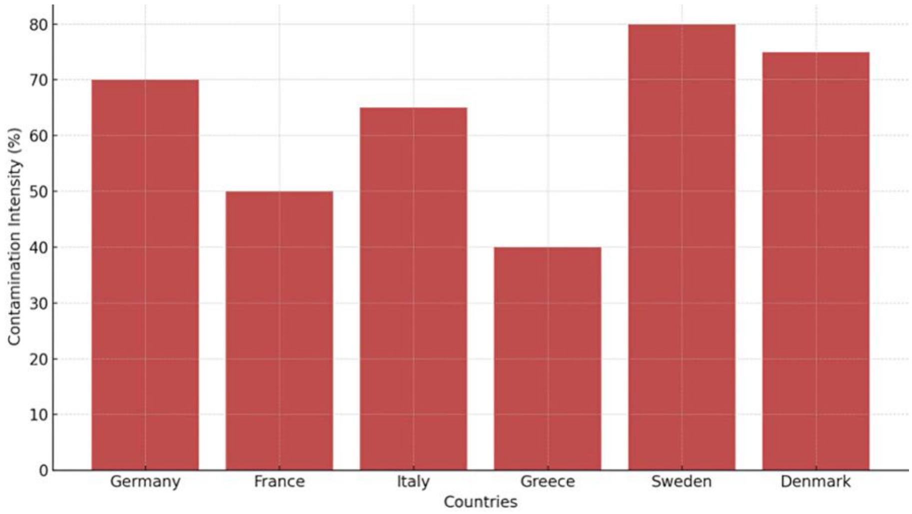


**Figure B3.** Geographic distribution of PFAS contamination in Europe (aggregated from Goldenman et al., 2019 and EFSA, 2020)

### Chart 4: Timeframe for PFAS Remediation Methods

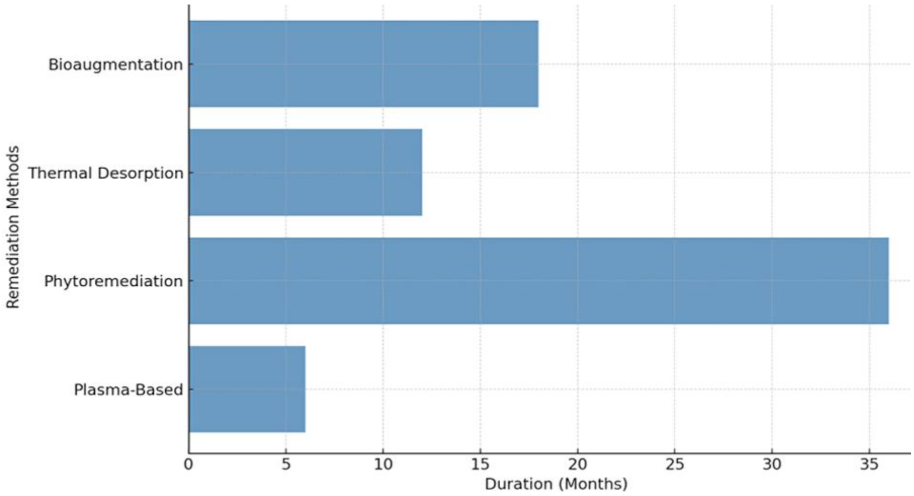


**Figure B4.** Timeframe for PFAS remediation methods (Ross et al., 2018 and European pilot project reports)

**Description:** A Gantt-style chart illustrating the estimated duration required for various remediation methods (e.g., plasma-based and phytoremediation).

### Chart 5: Effect of Remediation on Agricultural Productivity

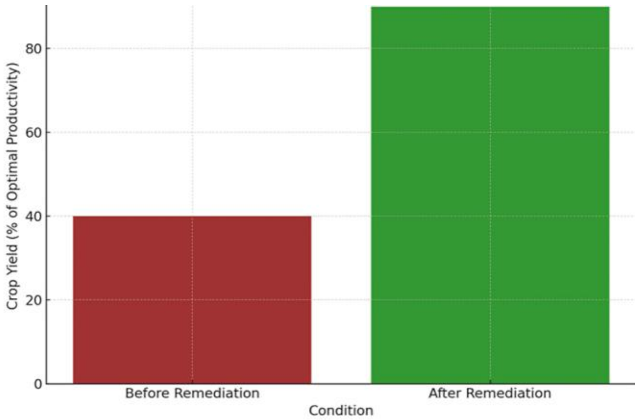


**Figure B5.** Effect of remediation on agricultural productivity (case studies from Northern Europe and the USA)

**Description:** A bar chart comparing crop yields before and after PFAS remediation efforts.

### Chart 6: Breakdown of Remediation Costs

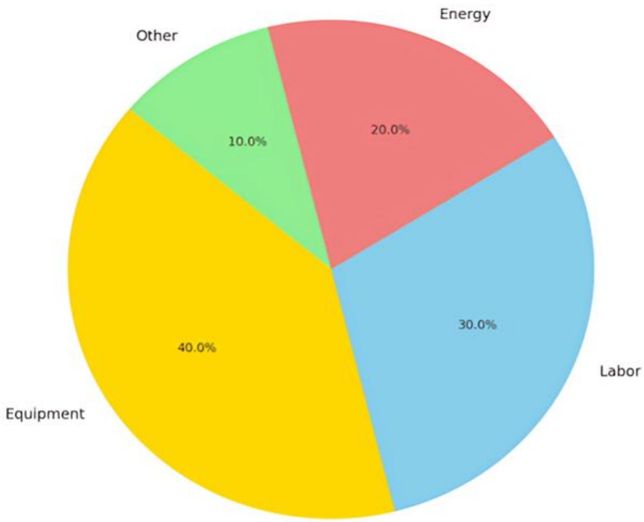


**Figure B6.** Breakdown of remediation costs (Goldenman et al., 2019)

**Description:** A pie chart detailing the allocation of remediation costs into equipment, labor, and other factors

### Chart 7: Public Awareness and Policy Implementation

**Description:** A bar chart comparing public awareness of PFAS risks and policy implementation effectiveness across regions.

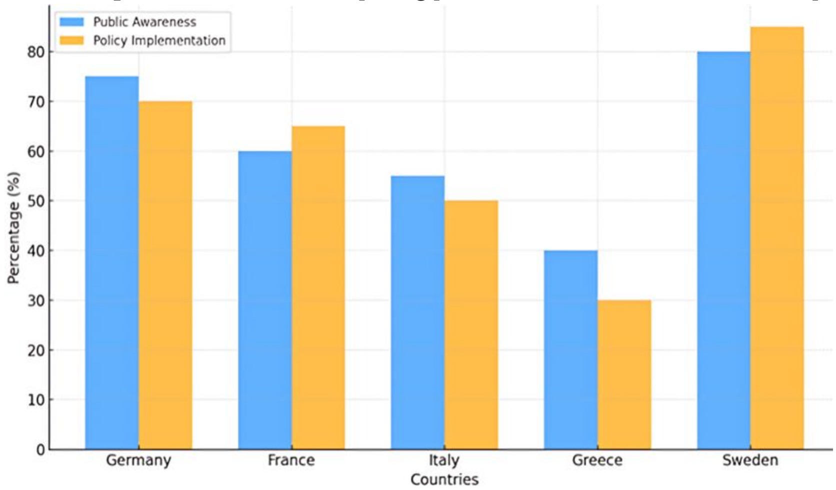


**Figure B7.** Public awareness and policy implementation (surveys by the European Commission and ATSDR, 2020)

### Chart 8: Funding Opportunities and Policies Across Regions

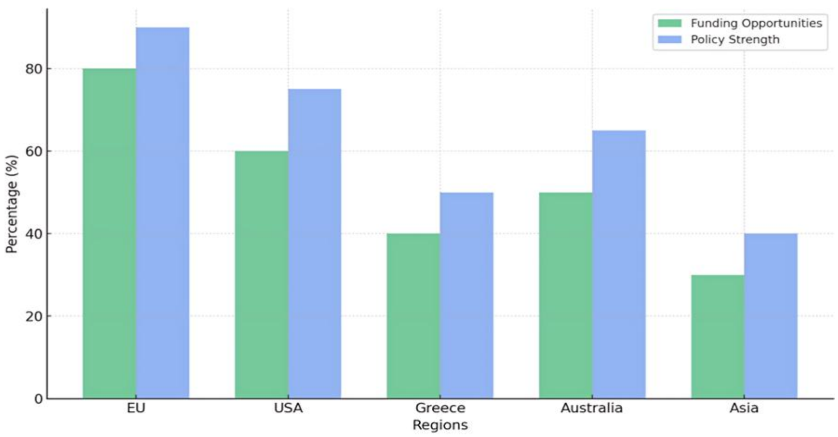


**Figure B8.** Funding opportunities and policies across regions (European green deal, Horizon Europe, and EPA PFAS initiatives)

**Description**: A grouped bar chart comparing funding availability and policy strength for PFAS remediation in regions like the EU, the USA, and Greece.

### Chart 9: Comparative PFAS Contamination Levels by Region

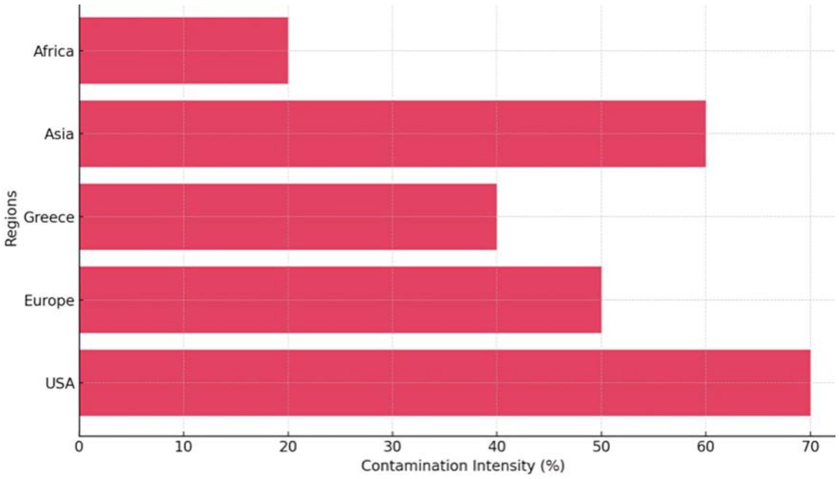


**Figure B9.** Comparative PFAS contamination levels by region (ATSDR, 2020 and C8 Health Project, 2013)

**Description:** A horizontal bar chart showing contamination intensity in global regions, including the USA, Europe, and Asia.

### Chart 10: Remediation Technology Adoption Across Regions

**Description:** A bar chart showing remediation technology adoption rates across regions.

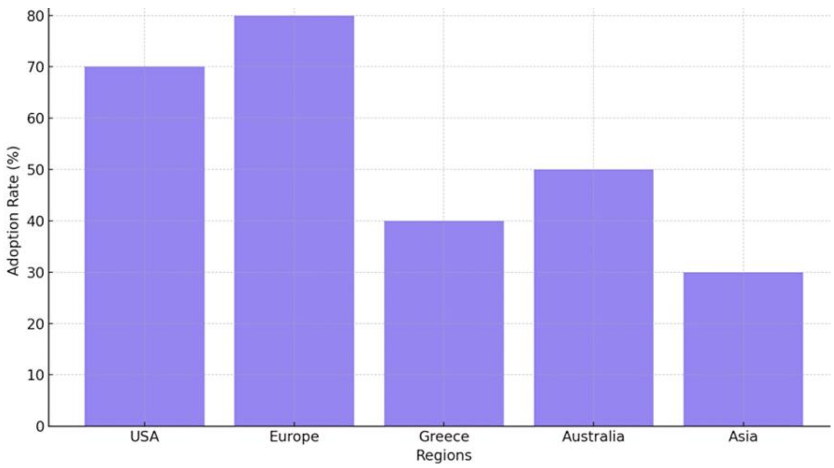


**Figure B10.** Remediation technology adoption across regions (Goldenman et al., 2019)

### Chart 11: Contamination vs. Crop Yield Impact Over Time

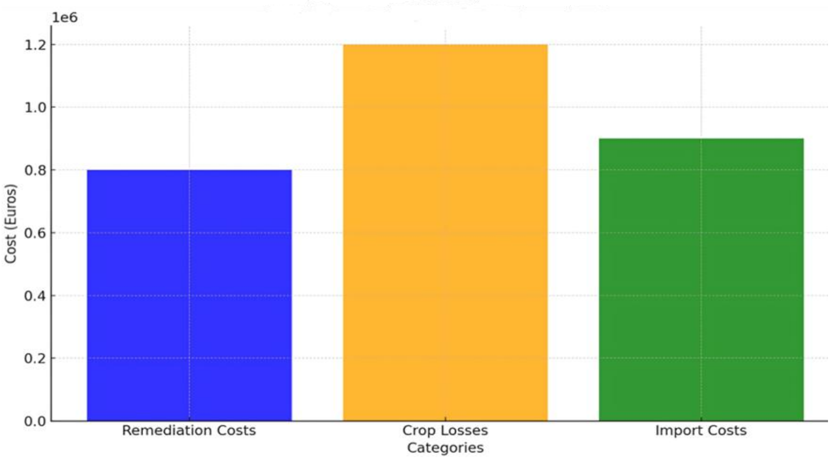


**Figure B11.** Contamination vs. crop yield impact over time (Goldenman et al., 2019)

**Description:** A bar chart comparing remediation costs with economic losses from contamination.

### Chart 12: Projections of PFAS Spread Without Intervention

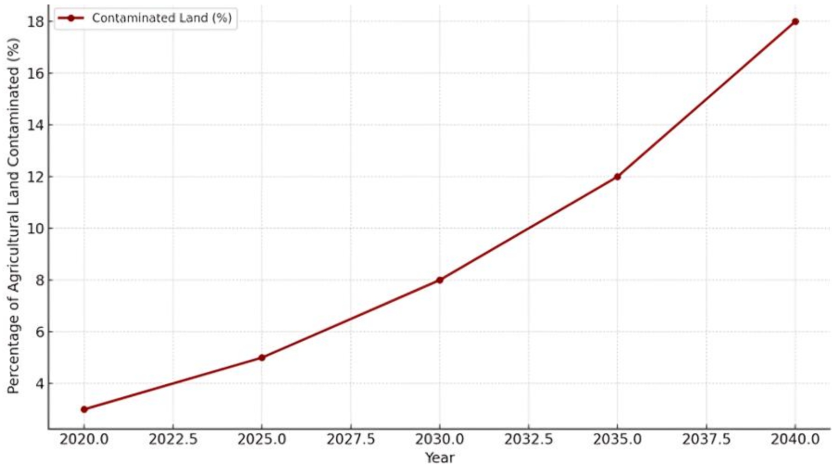


**Figure B12.** Projections of PFAS spread without intervention (modeled from trends in ATSDR, 2020)

**Description:** A line chart projecting the spread of PFAS contamination over two decades without intervention.

### Chart 13: Policy and Public Engagement Metrics

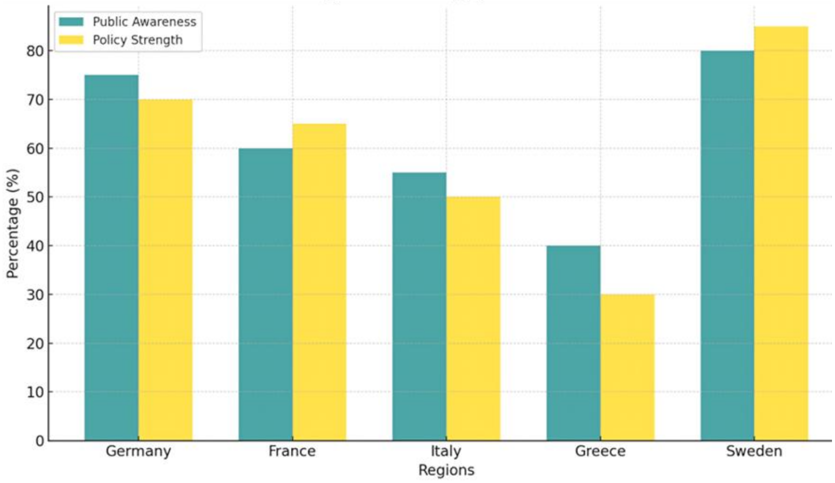


**Figure B13.** Policy and public engagement metrics (European Commission, 2020 and ATSDR, 2020)

**Description:** A bar chart comparing public awareness of PFAS risks and policy implementation effectiveness across regions.

### Chart 14: Global Comparison of PFAS in Food Supply

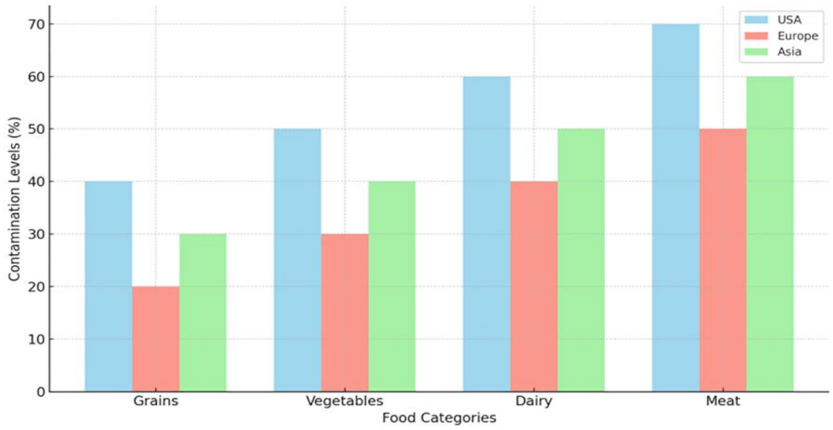


**Figure B14.** Global comparison of PFAS in food supply (EFSA, 2020 and ATSDR, 2020)

**Description:** A stacked bar chart comparing contamination levels in food categories across regions.

### Chart 15: Simplified European PFAS Contamination Heatmap

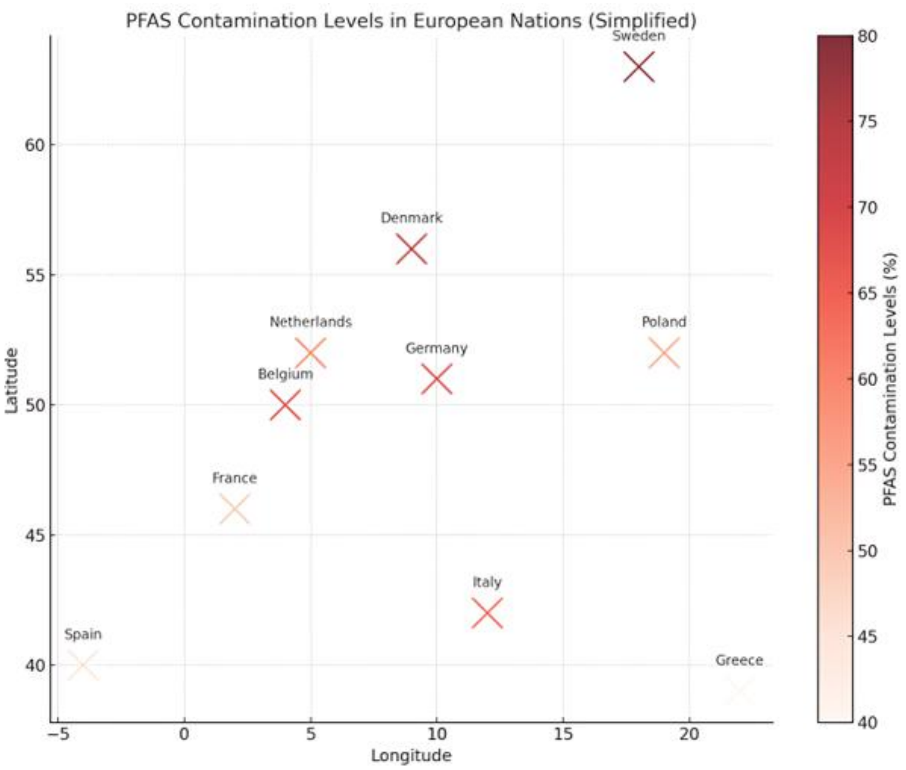


**Figure B15.** Simplified European PFAS contamination heatmap (aggregated from Goldenman et al., 2019)

**Description:** A geographic heatmap showing PFAS contamination levels across European countries.

### Applications

- **Field testing:** Farmers and environmental agencies use handheld fluorescence detectors for rapid on-site testing.
- **Remediation feedback:** Biomarker technology monitors the effectiveness of PFAS remediation techniques in real-time.

**Innovative use case:** A pilot study deployed a GFP-expressing *pseudomonas putida* strain to detect PFAS in groundwater samples. The system achieved detection limits as low as 10 ng/L, surpassing conventional analytical methods in cost-efficiency (Rahman et al., 2019).

### Integration of AI Mapping and Biomarker Technology

The combination of AI mapping and biomarker technology creates a robust detection framework. For instance:

1. AI mapping identifies broad contamination trends.
2. Biomarker technology provides localized, high-resolution data.
3. Integration improves accuracy by validating AI predictions with biomarker results.

### Algorithm for Integrated Approach

1. **Data fusion**
   - Combine geospatial data ($D_g$) with biomarker fluorescence data ($D_b$) https://www.codecogs.com/eqnedit.php?latex=(D_b) - 0using a weighted Bayesian approach: $P(C|D_g, D_b) = \frac{P(D_g|C)P(D_b|C)P(C)}{P(D_g)P(D_b)}$, where $P(C|D_g, D_b)$ is the posterior probability of contamination given the data.
2. **Visualization**
   - Generate contamination heatmaps with overlays of biomarker results to validate AI predictions.

### Advantages of Advanced Detection Tools

1. **Real-time monitoring:** Enables dynamic tracking of contamination spread.
2. **Cost-effectiveness:** Reduces reliance on expensive laboratory testing.
3. **Scalability:** Applicable across various agricultural and environmental settings.

### Soil Preparation

1. **Ultrasound-assisted pre-treatment**
   - **Mechanism:** High-frequency ultrasonic waves (20-100 kHz) break soil aggregates, increasing the surface area accessible for PFAS extraction. This process disrupts the soil structure and releases PFAS molecules bound to organic and inorganic particles.
   - **Advantages**
     - Improves the efficiency of subsequent remediation techniques.
     - Reduces treatment time by enhancing contaminant mobility.
   - **Process**
     - Soil is saturated with a solvent or water.
     - Ultrasonic probes generate cavitation bubbles that collapse, creating localized high temperatures and pressures.
     - PFAS molecules detach from soil particles and dissolve in the liquid phase.
   - **Key applications**
     - Effective for fine-grained soils like clay.
     - Suitable for pre-treating soils before electrokinetic or adsorption methods (Rahman et al., 2014).
2. **Electrokinetic methods**
   - **Mechanism:** Electrodes are inserted into the soil to create an electric field. PFAS molecules, being charged or polar, migrate towards the electrodes (electromigration) or are transported by water flow (electro-osmosis).
   - **Advantages**
     - Targets PFAS molecules deeply embedded in the soil.
     - Minimal soil disruption.
   - **Process**
     - Install electrodes at strategic locations.
     - Apply a low-voltage electric field (typically 1–5 V/cm).
     - Collect PFAS molecules at electrodes or transport them to an extraction zone.
   - **Challenges**
     - High energy consumption.
     - Requires careful control of soil moisture and pH (Ross et al., 2018).

### PFAS Removal Techniques

1. **Thermal desorption**
   - **Mechanism:** Soil is heated to temperatures between 300–600°C, causing PFAS molecules to volatilize. The gaseous PFAS are captured using cryogenic traps or activated carbon filters.
   - **Advanced techniques**
     - Solar-powered thermal systems to reduce energy costs.
     - Induction heating for precise temperature control.
   - **Limitations**
     - Energy-intensive.
     - Risk of incomplete removal if not properly controlled (Zhao et al., 2018).
2. **Plasma-based remediation**
   - **Mechanism:** Cold plasma, generated by applying a high-voltage electric field to a gas, produces reactive species like electrons and radicals. These species break the strong carbon-fluorine bonds in PFAS molecules.
   - **Process**
     - Plasma is applied to soil or PFAS-contaminated water.
     - Reactive species degrade PFAS into harmless byproducts like CO2_2 and HF.
   - **Advantages**
     - Non-invasive and highly effective.
     - No secondary pollutants.
   - **Challenges**
     - Requires specialized equipment.

    - Limited scalability for large, contaminated areas (Rahman et al., 2014).

3. **Adsorption**
    - **Mechanism:** PFAS molecules adhere to the surface of adsorbents like functionalized graphene oxide, zeolites, or biochar.
    - **Innovative adsorbents**
        - Functionalized graphene oxide for high PFAS affinity.
        - Biochar is modified with surfactants to enhance adsorption capacity.
    - **Applications**
        - Used as a standalone method or in combination with chemical washing.
    - **Challenges**
        - Disposal of spent adsorbents.
        - Lower efficiency for long-chain PFAS (Goldenman et al., 2019).
4. **Bioaugmentation**
    - **Mechanism:** Engineered microbes degrade PFAS into non-toxic components through metabolic pathways.
    - **Process**
        - Genetically modify microorganisms to express enzymes targeting PFAS bonds.
        - Introduce microbes into contaminated soil or water.
        - Monitor degradation byproducts.
    - **Key microorganisms**
        - *Pseudomonas putida* engineered for PFAS biodegradation.
        - Native bacteria are enhanced for metabolic efficiency (Liu et al., 2019).
5. **Phytoremediation**
    - **Mechanism:** PFAS-accumulating plants like willows and poplars extract contaminants from soil and water through their root systems.
    - **Advantages**
        - Eco-friendly and cost-effective.
        - Restores soil fertility over time.
    - **Challenges**
        - Requires long treatment periods.
        - Limited to shallow contamination zones.