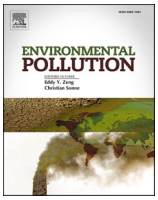
Environmental Pollution 333 (2023) 122038

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol



Phytoextraction of per- and polyfluoroalkyl substances (PFAS) and the influence of supplements on the performance of short–rotation crops☆

Winnie Nassazzi [a,*], Tien-Chi Wu [a], Jana Jass [b], Foon Yin Lai [a], Lutz Ahrens [a]

[a] Department of Aquatic Sciences and Assessment, Swedish University Agricultural Sciences (SLU), Box 7050, SE-750 07, Uppsala, Sweden
[b] The Life Science Center - Biology, School of Science and Technology, Örebro University, SE-701 82, Örebro, Sweden

ARTICLE INFO

Keywords:
Sunflower
Mustard
Hemp
Pollution
Phytoremediation

ABSTRACT

Per- and polyfluoroalkyl substances (PFAS) are anthropogenic compounds threatening water quality and food safety worldwide. Phytoremediation is a nature-based, cost-effective, and scalable solution with high potential for treating PFAS-contaminated sites. However, there is a large knowledge gap regarding choice of plant species and methods to enhance performance. This study assessed the PFAS phytoextraction potential of sunflower (*Helianthus annuus*), mustard (*Brassica juncea*), and industrial hemp (*Cannabis sativa*) in a greenhouse experiment, using inorganic fertilizer and a microbial mixture as supplements. PFAS concentrations were measured using UPLC-MS/MS, and bioconcentration factors for different plant tissues and removal efficiency were determined. Perfluoroalkyl carboxylic acid (PFCA) accumulation was 0.4–360 times higher than that of perfluoroalkyl sulfonic acid (PFSA) homologues of similar perfluorocarbon chain length. Inorganic fertilizer significantly ($p < 0.001$) reduced PFAS concentration in all plant tissues, whereas the microbial mixture tested did not affect PFAS concentration. PFAS uptake ranged from 0.2 to 33% per crop cycle. Overall, the potential number of crop cycles required for removal of 90% of individual PFAS ranged from six (PFPeA) to 232 (PFOA) using sunflower, 15 (PFPeA) to 466 (PFOS) using mustard and nine (PFPeA) to 420 (PFOS) using Hemp. In this study, the percentage of PFAS removal by plants was determined, and an estimation of the time required for PFAS phytoextraction was determined for the first time. This information is important for practical phytoremediation applications.

1. Introduction

Mass contamination of land with per- and polyfluoroalkyl substances (PFAS) mainly occurs from use of contaminated biosolids, firefighting activities using PFAS-containing aqueous film-forming foams (AFFF), landfilling, and atmospheric deposition. The contaminated land becomes a hotspot and source of PFAS for other parts of terrestrial and marine ecosystems (Hamid et al., 2018; Bolan et al., 2021a). Thus remediation remains a vital measure for managing the fate of PFAS at newly and historically contaminated sites. A wide array of PFAS remediation techniques are being developed and assessed (Naidu et al., 2020).

Phytoremediation is the utilization of plants to accumulate (phytoextraction), immobilize (phytostabilization), or destroy (phytodegradation) pollutants in a target medium (EPA, 2000). This technique is potentially useful for managing PFAS-contaminated sites (Kavusi et al., 2023). PFAS in plants have received much attention, as they are a potential hazard to human health. Some studies have focused on the uptake and transportation of perfluoroalkylacids (PFAA) and the degradation and uptake of PFAS precursors and their metabolites in edible plants (Bizkarguenaga et al., 2016; Blaine et al., 2014; Wen et al., 2014). Other studies have examined the phytotoxicity of PFAS by investigating the effects on plant growth, biomass, and various enzymes and genes (Chen et al., 2019; Zhang et al., 2019a). However, few studies have examined the potential of plants as a PFAS remediation strategy, although various review articles on the topic have been published (Kavusi et al., 2023; Lesmeister et al., 2021; Mayakaduwage et al., 2022).

Plants differ in their ability to accumulate PFAS and the success of a phytoremediation program is strongly determined by the plant species used (Mench et al., 2010; Ghisi et al., 2019). The potential of phytoremediation was first highlighted in a study investigating the fate of PFAS in plant species at a former firefighting site, where removal of up to 1.4 g of 26 PFAS per year was estimated for both silver birch and pine

☆ This paper has been recommended for acceptance by Jiayin Dai.

* Corresponding author.
E-mail address: winnie.nassazzi@slu.se (W. Nassazzi).

https://doi.org/10.1016/j.envpol.2023.122038
Received 12 April 2023; Received in revised form 2 June 2023; Accepted 12 June 2023
Available online 13 June 2023

(Gobelius et al., 2017). A few subsequent studies have investigated the phytoremediation potential of plant species such as reed grass in wetlands (30–50% removal), *Juncus sarophorus* (9–11% PFOS removal), and other woody and herbaceous species in a greenhouse experiment (Huff et al., 2020; Zhu et al., 2022; Ferrario et al., 2022). Thus, there is a need to identify plant species with good ability to accumulate PFAS. Sunflower, mustard, and hemp have been used previously in heavy metal phytoremediation programs, mainly for their high biomass production, tolerance to environmental stress, and ability to hyperaccumulate contaminants (Nehnevajova et al., 2005; Rathore et al., 2019; Todde et al., 2022). These promising plant species need to be assessed for their phytoextraction potential when exposed to a wide range of PFAS prior to field application.

Furthermore, improving the plant growing environment increases accumulation of contaminants in plants (Vangronsveld et al., 2009; Bolan et al., 2021b), through increased bioavailability of the contaminants in the growing medium or increased plant survival and vigor (Mench et al., 2010; Vangronsveld et al., 2009; Mench et al., 2009). For example, aeration has been shown to increase the PFAS phytoextraction potential of duckweed grown on deionized water at pH 2.3 by up to 80% (Zhang and Liang, 2020). Soil additives such as chelating agents, fertilizers, and microbial supplements have been tested, especially at sites with heavy metal contamination (Radziemska et al., 2021; Wang et al., 2021; Haider et al., 2021). Application of supplements could increase plant biomass and water uptake which could in turn increase PFAS uptake, especially water-soluble PFAS. However, to our knowledge, no previous study has assessed the effect of soil supplements (i.e., inorganic fertilizers and microorganisms) on plant accumulation of PFAS.

This study evaluated the PFAS phytoextraction potential of three short rotation plants (sunflower (*Helianthus annuus*), mustard (*Brassica juncea*), and industrial hemp (*Cannabis sativa*)) in a pot experiment within a greenhouse set-up. Specific objectives were to: (i) determine PFAS concentrations and distribution in the different plants, (ii) evaluate the effect of inorganic fertilizer and a microbial supplement on PFAS uptake in the plants, (iii) estimate PFAS removal by the plants, and (iv) predict temporal changes in the concentrations of selected PFAS in soil hosting the different plant species.

2. Materials and methods

2.1. Chemicals

The target analytes comprised: 10 perfluoroalkyl carboxylic acids (PFCA), namely perfluorobutanoic acid (PFBA), perfluoropetanoic acid (PFPeA), perfluorohexanoic acid (PFHxA), perfluorohepatanoic acid (PFHpA), perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA), perfluorodecanoic acid (PFDA), perfluoroundecanoic acid (PFUnDA), perfluorododadecanoic acid (PFDoDA), and perfluorotetradecanoic acid (PFTeDA); three perfluoroalkyl sulfonic acids (PFSA), namely perfluorobutane sulfonate (PFBS), perfluorohexane sulfonate (PFHxS), and perfluorooctane sulfonate (PFOS); and one perfluorooctanesulfonamide (FOSA) (Table S1 in Supporting Information (SI)). Nine mass-labelled internal standards (IS) were used ($^{13}C_4$-PFBA, $^{13}C_2$-PFHxA, $^{13}C_4$-PFOA, $^{13}C_5$-PFNA, $^{13}C_2$-PFDA, $^{13}C_2$-PFUnDA, $^{18}O_2$-PFHxS, $^{13}C_4$-PFOS, and $^{13}C_8$-FOSA) (Table S2 in SI). All above-mentioned compounds (with purity ≥99% were obtained from Wellington Laboratories (ON, Canada).

Methanol, acetonitrile, ammonium acetonitrile, and formic acid of high analytical grade were obtained from Sigma Aldrich (USA). Ultrapure water was obtained from a Milli-Q Advantage Ultrapure water purification system coupled with a 0.22 μm Millipak Express membrane and LC-Pak polishing unit from Merck Millipore (Billerica, USA).

2.2. Experimental design

The pot experiment was conducted in a greenhouse at the Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden, with temperature of 22 °C during the day and 18 °C at night, light/dark cycle set to 16/8 h, light intensity 150 μmol, and 50–60% relative humidity. The experiment had a 3 x 4 factorial design, with three plants (sunflower, mustard, hemp) and four soil supplements (a microbe mixture, fertilizer, fertilizer + microbes, and a control (no fertilizer or microbes)) (Fig. 1). The growing medium consisted of organic potting soil (S-jord garden soil, Hasselfors company, Sweden) spiked to achieve a theoretical concentration of 1 mg kg^{-1} for each PFAS (for details, see text in SI). The spiked concentration is environmentally relevant and has been reported at various contaminated sites worldwide (Brusseau et al., 2020). Measured PFAS concentrations in soil at time point 0 was 1.5 ± 0.9 mg kg^{-1} for each PFAS. Seeds of sunflower, mustard, and hemp were pre-germinated for six weeks, and then transplanted (one per pot) in plastic pots with dimensions 13.7 x 13.7 × 23 cm (L x W x H) and 3 L volume, and containing 1 kg wet weight (ww) of PFAS-spiked soil. Each 3 x 4 experiment was performed in triplicate, resulting in a total of 36 pots (Fig. 1).

Irrigation water containing supplements was applied ad libitum to all pots throughout the experiment. For the treatment with fertilizer, a fertilizer solution containing (g L^{-1}): 51 N, 10 P, 43 K, 4 S, 3 Ca, 4 Mg, 0.17 Fe, 0.20 Mn, 0.10 B, 0.03 Zn, 0.015 Cu and 0.004 Mo obtained from Wallco Plant Nutrition (Cederroth International, Sweden) was used. For the treatment with microbes, a commercial microbial supplement (Tarantula Beneficial Bacterial Liquid fertilizer) containing *Arthrobacter globiformis*, *Bacillus brevis*, *Bacillus coagulans*, *Bacillus licheniformis*, *Bacillus megaterium*, *Bacillus polymyxa*, *Bacillus pumilus*, *Bacillus subtilis*, *Bacillus thuringiensis*, *Bacillus thuringiensis canadiensis*, and *Paenibacillus polymyxa* was used. It was mixed with irrigation water in a ratio of 1:2 before application. For the fertilizer + microbes treatment, the microbial supplement was mixed with the fertilizer solution. Tap water was used to irrigate all control pots.

2.3. Sample preparation and analysis

All plants were harvested after three months of PFAS exposure and samples of each plant were divided into seeds, leaves, stem, and root. Water and soil samples were also collected. Preparation and extraction of plant and soil samples for PFAS was done using validated methods published elsewhere (Nassazzi et al., 2022) (details available in SI). Samples of irrigation water were extracted by solid phase extraction (SPE) using Oasis WAX cartridges (Waters, 150 mg, 6 mL, 30 μm) and the method can be found elsewhere (Gobelius et al., 2017). Branched isomers of PFOS and FOSA were quantified using the corresponding linear standards.

All samples were analyzed using an ultra-performance liquid chromatography-tandem mass spectrometer (UPLC-MS/MS) (Thermo Scientific Dionex Ultimate 3000 Pumps; TSQ Quantiva, Thermo Fisher Scientific, San Jose, CA USA). An Acquity UPLC BEH-C18 (2.1 × 50 mm, 1.7 μm particle size; Waters Corporation, Manchester, UK) analytical column was used for chromatographic separation. The data were evaluated using TraceFinder software (version 4.1, Thermo Fisher, USA) (details available in SI).

2.4. Quality control and assurance

Laboratory blanks, replicates, method detection limits (MDLs), linearity, and recovery were assessed. MDLs for plants were determined using a signal to noise ratio of 3 in matrix-spiked samples with a concentration of 5 ng g^{-1} dry weight (dw). The MDLs for water and soil samples were calculated based on average blank + 3xstandard deviation. A calibration curve with concentration ranging from 0.01 to 200 ng mL^{-1} for each PFAS was used for quantification. Correlation coeffients (R^2) of the calibration curve were used to determine the linearity. The relative recovery of the method was assessed using reference composite plant samples (pre-spike n = 3 and post-spike n = 3). The

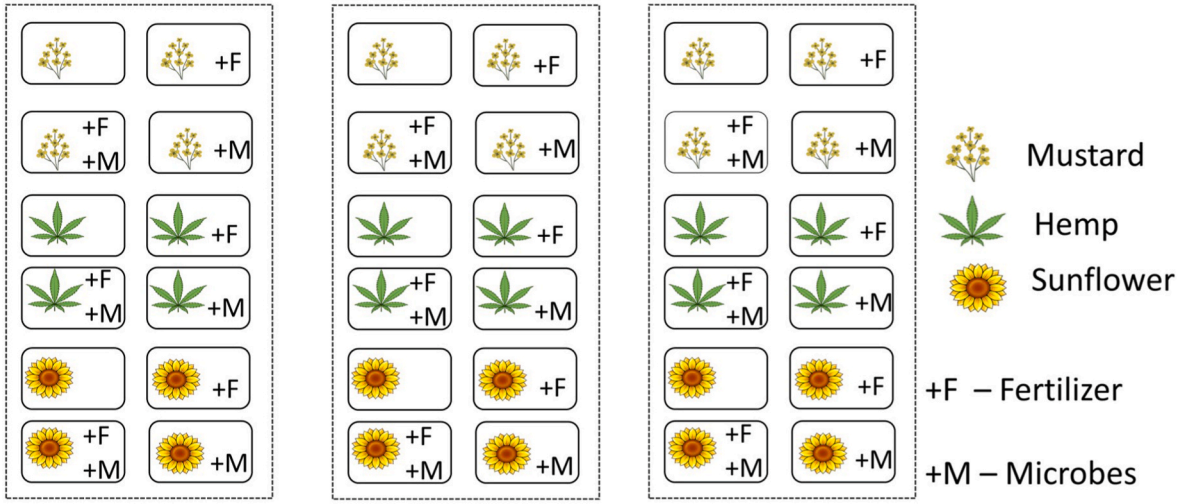


Fig. 1. Schematic diagram of the triplicate greenhouse experiment set-up of mustard, hemp, and sunflower pots, with and without fertilizer and microbe supplements.

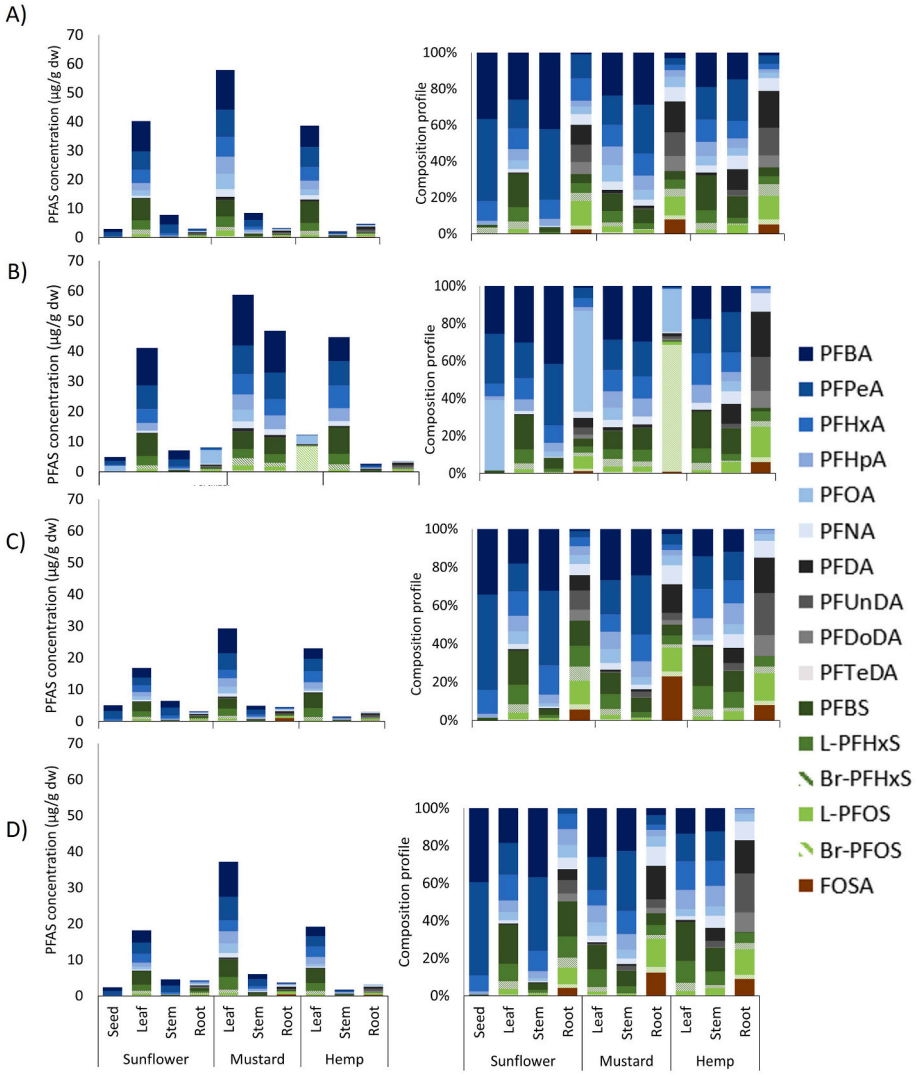


Fig. 2. Average PFAS concentration (µg g^{-1} dw) and composition profile (%) in different tissues (n = 3) of sunflower, mustard, and hemp grown in PFAS-spiked soil with different supplements: A) Untreated control, and supplementation with B) only microbes, C) both fertilizer and microbes, and D) only fertilizer.

composition of the reference samples can be found elsewhere (Nassazzi et al., 2022). Recoveries of the internal standards were also determined. Details on the MDLs, relative recovery values, and blank levels are available in Tables S3–S5 in SI.

2.5. Calculations

Plant concentration factors, representing the ability of different tissues (leaf, stem and root) to accumulate contaminants from soil, were calculated using the following equations:

$$\text{Leaf concentration factor (LCF)} = C_{leaf}/C_s \quad (1)$$

$$\text{Stem concentration factor (SCF)} = C_{stem}/C_s \quad (2)$$

$$\text{Root concentration factor (RCF)} = C_{root}/C_s \quad (3)$$

$$\text{Bioconcentration factor (BCF)} = C_p/C_s \quad (4)$$

where Cs is the PFAS concentration in soil (ng g^{-1} dw), C_{leaf}, C_{stem} and C_{root} is the PFAS concentration in the leaves, stem and root, respectively (ng g^{-1} dw), and C_p is the PFAS concentration in the whole plant (ng g^{-1} dw) at time of harvest.

Removal efficiency (r) was calculated as:

$$r = \frac{C_p\, M_p}{C_{si}\, M_s} \times 100 \quad (5)$$

where M_p is plant biomass (g dw), C_{si} is initial soil concentration (ng g^{-1} dw), and M_s is soil mass (g dw).

2.6. Statistics

Descriptive statistics (mean, standard deviation, and range), regression, correlation analyses, and data visualization were performed using GraphPad Prism (version 9.2.0 (332)). Statistical differences between means were evaluated using analysis of variance (ANOVA) at significance level $\alpha = 0.05$, using the R software.

3. Results and discussion

3.1. PFAS concentration in plants of the different species

Of the 14 target PFAS, 12 were detected in different tissues of sunflower, mustard, and hemp (Fig. 2, Tables S7–S8 in SI). ΣPFAS concentration was significantly higher (ANOVA, $p < 0.05$) in mustard than in sunflower and hemp in all treatments (Table S6 in SI). Without any supplement (control), mustard plants were observed to contain 2-7 times higher concentrations of some PFAS than sunflower (PFHpA, PFOA, PFNA, PFDA, PFUnDA, PFDoDA, PFOS, FOSA) or hemp (PFOA, PFDoDA, PFOS, FOSA). A previous study investigating PFAS accumulation in various plants, including sunflower and mustard, found that the concentration of six PFAS was 3–6 times higher in mustard than in sunflower. Studies on other plants have also reported differences in PFAS uptake with plant species and genotypes (Blaine et al., 2014; Gobelius et al., 2017; Xiang et al., 2018). Variations in PFAS uptake are caused by plant anatomy and physiological traits such as biomass, transpiration rate, growth rate, root composition, and exudates (Sheoran et al., 2016).

ΣPFAS concentrations were also significantly different ($p < 0.001$) between the plant tissue groups and generally decreased in the order: leaf > stem > root ≈ seed (sunflower only). In the control, ΣPFAS concentrations in sunflower were within the range 0.018–11 μg g^{-1} dw in leaves, 0.003–3.3 μg g^{-1} dw in stems, 0.029–0.41 μg g^{-1} dw in roots, and 0.004–1.3 μg g^{-1} dw in seeds. The ΣPFAS concentration range in mustard was 0.015–14 μg g^{-1} dw in leaves, 0.005–2.4 μg g^{-1} dw in stems, and 0.069–0.54 μg g^{-1} dw in roots. In hemp, the ΣPFAS concentration range was 0.0008–7.4 μg g^{-1} dw in leaves, 0.007–0.48 μg g^{-1} dw in stems, and 0.07–0.96 μg g^{-1} dw in roots.

In general, the concentration of individual PFAS in the three plant species decreased in the order: PFBA > PFPeA > PFBS > PFHxA > PFHpA > PFHxS > PFOA > PFNA > PFOS > PFDA > PFUnDA > FOSA > PFDoDA. FOSA was only detected in the roots. Short-chain PFCA (i.e., PFBA, PFPeA, PFHxA, PFHpA) were the predominant PFAS accumulated in sunflower seeds (95% of ΣPFAS), and leaf (57–62%) and stem (52–95%) tissues in all three plant species. Sunflower stems had a lower proportion of PFSA (3.7% of ΣPFAS) than stems of mustard (14%) and hemp (21%). In contrast, the composition profile of roots was dominated by PFSA (27–31% of ΣPFAS) and long-chain PFCA (32–52%) homologues in all three plant species. This is consistent with previous findings for other plant species (Gredelj et al., 2020; Krippner et al., 2015). Some studies have also reported presence of PFAS in seeds of various cereals such as maize, wheat, rye, and canola in different experimental set-ups (Krippner et al., 2015; Stahl et al., 2013; Stahl et al., 2009). The variation in PFAS composition of different plant parts suggests that water-soluble and mobile short-chain PFAS are transported in the plant during water uptake and transpiration, and accumulate in upper plant parts. Hence, short-chain PFAS dominated in leaves and stems.

Use of a supplement (fertilizers, microbes, or fertilizer + microbes) significantly ($p < 0.001$) affected ΣPFAS concentrations in plants. Fertilizer application (with or without microbes) significantly ($p < 0.001$) reduced the ΣPFAS concentration in all plant tissues, by on average 19% (roots) to 49% (foliage) (Fig. 2C and D). A previous study involving supplementation of lettuce, tomato, and maize with biosolids to meet their nitrogen requirement observed increased concentrations of PFBA and PFPeA at high biosolid application rates to the soil (4 times the agronomic nitrogen requirement) (Blaine et al., 2013). However, this could have been due to more PFAS being applied with increasing biosolids application, rather than an effect of nitrogen on PFAS uptake.

Supplementation with the microbial mixture did not significantly affect PFAS concentration in any of the plant species studied ($p > 0.05$) (Fig. 2B). The microorganisms applied possess pesticidal effects, and also the ability to increase soil fertility and plant tolerance to stress (Hashem et al., 2019; Dobrzyński et al., 2022). These traits can enhance plant growth and survival, and could potentially increase PFAS concentration in the plant. However, this was not observed under the experimental conditions in the present study. The effect of PFAS on soil microbial communities and microbial PFAS remediation in the presence and absence of plants has been discussed in previous studies (Zhang et al., 2019b; Arslan and Gamal El-Din, 2021), but no published data are currently available on the effect of plant-microbial interactions on PFAS accumulation. Inoculation of plants with microorganisms has been shown to enhance the concentration of heavy metals in plants (Jankong et al., 2007; Alves et al., 2022), but more research is needed on PFAS uptake in plants.

3.2. Plant tissue-specific concentration factors

The bioaccumulation factors for leaf (LCF), stem (SCF) and root (RCF) of the different species were evaluated. ΣPFAS accumulation was generally highest in the order leaves > stem > roots. Observed LCF values for individual PFAS ranged between 0.6 (PFUnDA) and 2092 (PFBA) for sunflower, 0.13 (FOSA) and 1816 (PFBA) for mustard, and 0.033 (PFDoDA) and 2671 (PFBA) for hemp. Observed SCF for individual PFAS ranged between 0.1 (PFUnDA) and 656 (PFBA) for sunflower, 0.17 (PFDoDA) and 365 (PFBA) for mustard, and 0.2 (PFDoDA) and 197 (PFPeA) for hemp. Observed RCF for individual PFAS ranged between 0.37 (PFHxS) and 42 (PFPeA) for sunflower, 0.27 (PFHxS) and 12 (PFBA) for mustard, and 0.97 (PFBS) and 11 (PFUnDA) for hemp PFAS (for details, see Tables S9–S11 in SI). Thus LCF was higher than SCF or RCF, which is similar to previous findings (Navarro et al., 2017; Lechner and Knapp, 2011). This study is the first to report LCF and SCF

for 12 different PFAS in sunflower, mustard, and hemp.

The actual plant tissue concentration factors were generally higher than those previously reported for various edible plants (Ghisi et al., 2019), grass (Yoo et al., 2011), and forest trees (Gobelius et al., 2017). This could indicate that sunflower, mustard, and hemp have higher PFAS accumulation and uptake efficiency than previously studied plant species at similar PFAS concentration. However, plant concentration factors are influenced by PFAS bioavailability which is controlled by the physicochemical properties of PFAS, soil and plant factors (Lesmeister et al., 2021). Our results also revealed that PFAS uptake is dominated by roots, in which dissolved contaminants together with nutrients and water can be acropetally transported through the transpiration stream and accumulated in the leaves (Collins et al., 2006).

Linear regression plots of log-transformed data showed a significant decrease in LCF and SCF for PFCA with increasing perfluorocarbon chain length for all plant species studied ($p < 0.05$) (Fig. 3). Each addition of a perfluorocarbon moiety (CF_2) led to a decrease of 0.3–0.5 log units in both LCF or SCF. This is consistent with trends reported for vegetables and grass (Blaine et al., 2013; Yoo et al., 2011; Felizeter et al., 2012), and demonstrates the reliance of PFAS uptake and transport on their physiochemical properties. PFAS bioavailability in the soil is predominantly influenced by compound mobility, which can be predicted using the soil sorption coefficient (K_d) (Nguyen et al., 2020). A higher K_d value results in increased sorption, due to increases in both hydrophobicity and lipophilicity. Thus with each CF_2 added, both the absorption and transport of PFAS are reduced (Collins et al., 2006; Felizeter et al., 2014).

The LCF and SCF values for PFSA showed similar dependence on perfluorocarbon chain length as seen for PFCA. However, plant tissue accumulation of PFCA was 0.4–360 fold higher than for PFSA homologues of similar perfluorocarbon chain length. Although PFOA and PFOS uptake was observed to be a non-competitive process, a previous study found higher accumulation of PFOA compared with PFOS in wheat straw grown on biosolids-amended soil (Wen et al., 2014), which is in agreement with the results in this study. This can be explained by the physicochemical properties of PFSA molecules, which have a larger structure and stronger sorption to surfaces than PFCA molecules of similar perfluorocarbon chain length (Higgins and Luthy, 2006). In this study, FOSA, which has been shown to have higher K_d than PFOS and PFNA (Nguyen et al., 2020), was mainly found in the roots of all plants investigated. This implies that FOSA was strongly sorbed to the roots, which limited its transportation to the upper parts of the plant.

With regard to RCF, a different relationship with perfluorocarbon chain length was found for PFCA (Fig. 4). A significant decrease in RCF

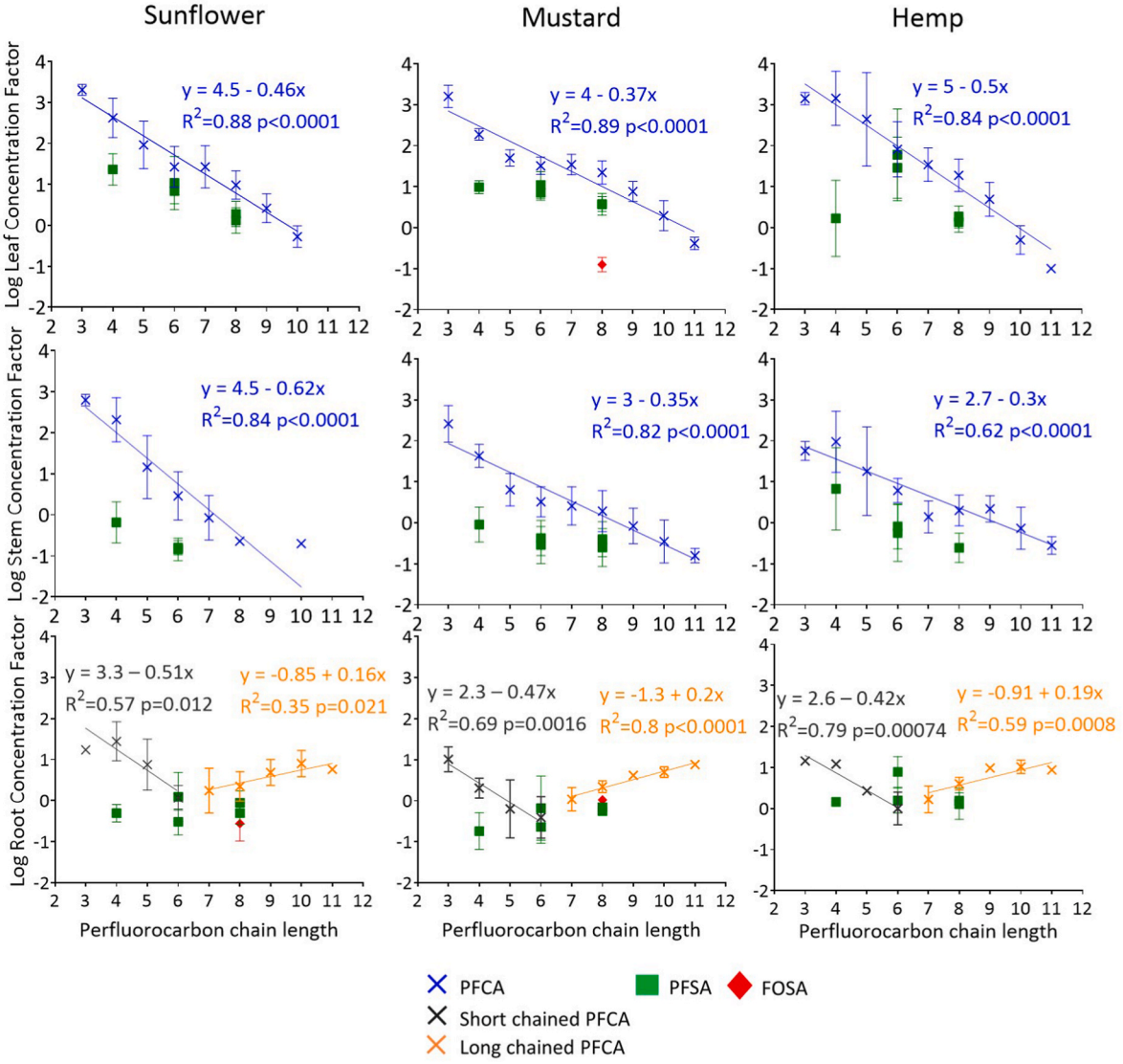


Fig. 3. Relationship between leaf concentration factor (LCF), stem concentration factor (SCF), and root concentration factor (RCF) and perfluorocarbon chain length for sunflower, mustard, and hemp plants grown on PFAS-spiked soil.

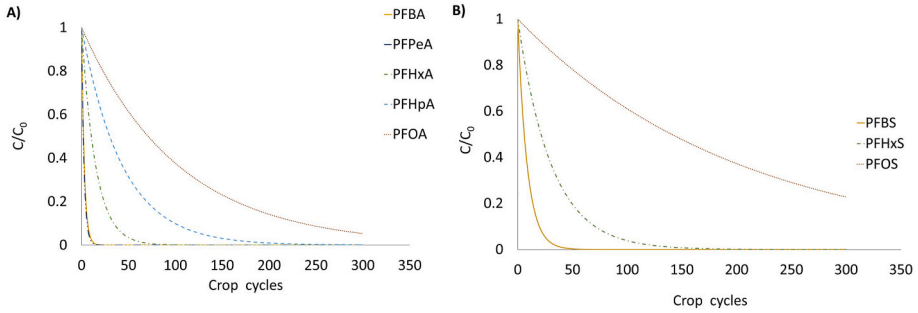


Fig. 4. Estimated number of crop cycles (1 crop cycle = 90 days) required to phytoextract the PFAS A) PFCA and B) PFSA from a contaminated site using sunflower.

with an increase in perfluorocarbon chain length was found for C_3 (PFBA) to C_6 (PFHpA) compounds ($p < 0.05$), but a significant increase for C_7 (PFOA) to C_{11} (PFDoDA) compounds ($p < 0.05$) in all plants. Thus RCF was lowest at C_6 (PFHpA) for all plants. A similar trend has been observed previously for hydroponically cultivated lettuce (*Lactuca sativa*) and for wheat (*Triticum aestivum*) in field experiments (Wen et al., 2014; Felizeter et al., 2012). The RCF values were also generally lower than both the LCF and SCF values. The low RCF observed for shorter-chain PFAS was probably due to their high mobility and continuous transportation to other plant tissues. Long-chain PFAS are structurally larger and more lipophilic than their short-chain counterparts (Buck et al., 2011), so limited amounts of long-chain PFAS are absorbed into the roots and there is limited transportation to other plant tissues (Costello and Lee, 2020). It should also be noted that all plant tissues in this study were thoroughly washed with water and MeOH (50:50) before analysis. Therefore, the results obtained mainly represent PFAS taken up by the roots, but it is possible that some PFAS were still sorbed onto root surfaces before washing and analysis. Studies using soil as the planting medium have generally found no relationship between RCF and chain length, especially at high PFAS concentrations (Blaine et al., 2014; Wen et al., 2014).

3.3. Species-specific accumulation

Bioconcentration factor, determined as the ratio of ΣPFAS concentration in the plant to ΣPFAS concentration in the soil at harvest, was used to assess and compare the overall PFAS accumulation and phytoextraction potential of the three plant species studied. Hemp had the highest BCF for ΣPFAS (0.05–1170), followed by sunflower (0.03–957) and mustard (0.19–590) (Tables S12–S13). BCF values >1 signify plant ability to accumulate a contaminant, while BCF values >10 indicate that the plant is a hyperaccumulator (Huff et al., 2020). Based on these thresholds, all three plant species tested were classified as hyperaccumulators of at least five compounds (PFBA, PFPeA, PFHxA, PFHpA, and PFDoDA). In addition, hemp was a hyperaccumulator of PFOA, PFNA, PFDA, PFBS, and PFHxS. A previous study assessing PFAS accumulation in both woody and herbaceous plants observed similar results, but found that sunflower only hyperaccumulated PFPeA among six compounds analyzed (Huff et al., 2020), in contrast to our results. In the same study, mustard was observed to have higher BCF values for all compounds except PFPeA than the BCF values found in our study. Other studies on vegetables and forest plants also report variations in plant BCFs, which they attribute to plant chemical composition (lipid:protein content) and the PFAS fingerprint of the growing medium (Gobelius et al., 2017; Xiang et al., 2018; Blaine et al., 2013; Wen et al., 2013).

3.4. Total plant burden

Total plant burden was determined as the absolute weight (in μg) of PFAS in plant biomass. Sunflower had the highest ΣPFAS burden (819 ± 262 μg per plant), followed by hemp (732 ± 111 μg). Despite mustard having high PFAS concentrations in plant tissues, it had the lowest ΣPFAS burden (417 ± 97 μg), which can be explained by the lower biomass of mustard plants compared with sunflower and hemp. At the time of harvest, hemp had not reached flowering, whereas sunflower and mustard had flowered. Therefore, the phytoextraction potential of hemp may not have been fully exploited in this study as plants probably did not attain full maturity. Mass PFAS distribution in different tissues was relatively similar between the plants (Table 1). Of the total PFAS mass (μg) found in the plants, C_3–C_9 perfluorocarbon PFAS were dominant in the shoot system (leaves and stem), while C_{10}–C_{11} perfluorocarbon PFAS were dominant in the root system, as also indicated by the LCF, SCF, and RCF values. The PFAS dominance in the shoot system could have positive implications for phytoremediation, as shoots are easier to harvest and complete root harvest can be difficult to achieve. Mustard and sunflower had 4-6 times more short-chain PFAS in their stems than hemp, which accumulated >90% of this group of compounds in the leaves. Only a small fraction (≤6%) of C_3–C_6 perfluorocarbon PFAS accumulated in seeds in sunflower.

3.5. Effect of fertilizer and microbial supplements

Plant response to the different supplements was examined using plant biomass, PFAS concentration in plant tissues, and effect on total plant burden. Sunflower (281 g ww, 54 g dw) and hemp (140 g ww, 47 g dw) produced more average biomass per plant than mustard (12 g ww, 7.9 g dw). Mustard had a much higher proportion of dry matter (up to 68%) than sunflower (19%) and hemp (34%). Addition of fertilizer was observed to increase plant biomass by 2- to 3-fold in sunflower and hemp, but slightly reduced the dry mass proportion for both species (from 34 to 18% for hemp, and from 19 to 15% for sunflower). There were no observable changes in biomass and dry matter content for mustard. The increase in biomass in sunflower and hemp did not result in an increase in PFAS accumulation. As previously noted (section 3.1), fertilizer application led to reduced PFAS concentration in plants. However, the greater biomass obtained for plants treated with fertilizer led to no significant difference in absolute PFAS mass in plants (ANOVA, $p < 0.05$) (Table S14 in SI). The mechanism for reduction of PFAS concentration in plants due to addition of inorganic fertilizers is not fully understood. However, possible reasons include (i) increased cation concentration that could reduce PFAS bioavailability (Cai et al., 2022), or (ii) increased water uptake, which led to dilution of contaminants in the plant. In the present study, use of the microbial supplement had no observable effects on biomass, dry matter content, or plant burden of PFAS. This is consistent with previous findings of increased plant biomass, but reduced heavy metal concentration, in rye (*Secale cereale*) supplemented with both inorganic fertilizers and microbes at a contaminated site in China (Chen et al., 2023). Further studies using metagenomics and root microscopy are needed to identify potential synergistic effects between specific organisms and plants, and their effect on PFAS accumulation.

Table 1
Distribution of individual PFAS based on the total burden in tissues of sunflower, mustard, and hemp, expressed as a percentage of their total PFAS uptake. A color gradient from green (highest) to red (lowest) represents the mass distribution.

	Sunflower (%)				Mustard (%)			Hemp (%)		
Compound	Seed	Leaf	Stem	Root	Leaf	Stem	Root	Leaf	Stem	Root
PFBA	4	61	35	0	64	36	0	94	6	0
PFPeA	6	46	47	1	56	43	1	91	9	0
PFHxA	3	65	30	2	67	32	1	94	6	0
PFHpA	2	76	21	1	73	26	1	94	5	1
PFOA	0	91	6	2	77	21	2	93	6	1
PFNA	0	88	5	7	71	24	5	84	13	3
PFDA	0	63	0	37	55	23	22	54	33	14
PFUnDA	0	18	2	81	28	19	53	16	41	43
PFDoDA	0	0	0	100	6	7	87	2	21	78
PFBS	0	94	5	1	72	27	2	95	5	1
L-PFHxS	0	95	4	2	79	19	3	95	3	1
Br-PFHxS	3	92	2	3	87	7	7	95	2	3
L-PFOS	0	86	1	13	71	19	10	75	15	9
Br-PFOS	0	89	0	11	75	17	8	88	0	12
FOSA	0	0	0	100	12	0	88	0	0	100

3.6. Phytoremediation potential

All plants grew without any visible abnormalities (such as chlorosis, stunting, or reduction in weight) despite the presence of PFAS, with or without supplements. This indicates that the species studied had high tolerance to PFAS contamination and could grow at PFAS-contaminated sites. Other studies have also observed no negative impact of PFAS on plant growth (Gobelius et al., 2017; Zhao et al., 2016), except at very high concentrations (e.g., 5–20 mg L^{-1}) (Chen et al., 2019; Wen et al., 2013). This is $\geq$ 10 times higher than the concentration used in this study and not realistic for PFAS-contaminated sites (Gobelius et al., 2017).

Individual PFAS uptake efficiency from soil was 0.2–33% for sunflower, 0.2–14% for mustard, and 0.2–24% for hemp, based on the PFAS concentrations in soil and all plant tissues (Table S15 in SI). For all plants, PFUnDA and PFDoDA had the lowest PFAS removal by plants, while the highest PFAS uptake efficiency was observed for PFPeA (14–33%), followed by PFBA (12–30%), PFBS (3.2–12%), PFHxA (3.7–6.8%), PFOA (1–1.1%), PFHxS (1.5–3.3%) and PFOS (0.4–0.5%).

The phytoremediation potential of the three plant species for individual PFAS was predicted based on crop cycles (1 crop cycle = 90 days of PFAS exposure), assuming constant PFAS uptake for subsequent crop cycles. Previous studies have reported an effect of PFAS concentration in the growing medium (e.g., water and soil) and PFAS concentration in plant tissues (Gobelius et al., 2017; Wen et al., 2013). However, there is no consensus on the influence of PFAS concentration on PFAS removal efficiency (Lesmeister et al., 2021; Wen et al., 2013). We, therefore, estimated the number of crop cycles required to phytoremediate soil with a similar PFAS concentration as tested in this experiment using sunflower (highest PFAS removal) and mustard (lowest PFAS removal). PFAS concentration after a cycle of phytoextraction was determined as C_i - rC_i, where C_i is initial PFAS concentration and r is percentage PFAS removal by the plant. PFAS concentration and number of cycles required were determined using an iterative approach.

For sunflower, shorter-chain PFAS required fewer crop cycles to reach 90% PFAS removal from soil. PFBA and PFPeA were estimated to require 6–7 crop cycles, PFHxA 34, PFHpA 96, PFOA 232, PFBS 20, PFHxS 70, and PFOS 458 crop cycles (Fig. 4 and Table S16 in SI). Estimated crop cycles required when using hemp increased as follows: PFPeA required 9 crop cycles, PFBA 14, PFBS 16, PFHxA 32, PFHxS 66, PFHpA 68, PFOA 165, PFOS 420. Similar findings were made for mustard, but this species generally was estimated to require more cycles than sunflower, i.e., PFBA required 19 crop cycles, PFPeA 15, PFHxA 60, PFHpA 100, PFOA 192, PFBS 20, PFHxS 70, and PFOS 466 crop cycles. The results highlighted the suitability of the method for media dominantly contaminated with short-chained PFAS. Furthermore, the results suggest that sunflower is a more suitable plant than mustard for phytoremediation of PFAS-contaminated sites, however, field experiments are required to verify these findings.

4. Conclusions

This study investigated the PFAS phytoextraction potential of sunflower, mustard, and hemp in greenhouse experiments. The results showed differences between the plant species in phytoremediation and PFAS-specific accumulation in different tissue types. All three species hyperaccumulated at least five of the target PFAS, and are thus potentially suitable for phytoremediation in the field. Treatments to optimize the phytoextraction potential of the species by using inorganic and microbial supplements gave only a limited improvement in PFAS uptake for all species. The estimated number of crop cycles required to remove individual PFAS from contaminated soil was lowest, i.e., removal efficiency was highest, for short-chain PFAS. This new information can be used in risk management and practical application of phytoremediation in the field. Harvested plant biomass can be used for energy production through which extracted PFAS can be degraded. However, life cycle analysis to determine and prevent potential negative environmental impacts of this process is needed for the future. Future studies should also examine other microbial species and the effects of microbial interactions with plants.

Credit author statement

Winnie Nassazzi: Conceptualization, Methodology, Data curation, Formal analysis, Writing-original draft, and editing. Tien-Chi Wu: Investigation, Data curation and Writing-review and editing, Jana Jass: Methodology, Writing-review and editing, Supervision, Foon Yin Lai: Conceptualization, Validation, Formal analysis, Writing-review and editing, Supervision. Lutz Ahrens: Conceptualization, Writing-review and editing, Supervision, Funding acquisition, and Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was part of the PhytoRem project, funded by the Swedish Geotechnical Institute (SGI) through the Tuffo program (1.1-1805-0352).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2023.122038.

References

Alves, A.R.A., Yin, Q., Oliveira, R.S., Silva, E.F., Novo, L.A.B., 2022. Plant growth-promoting bacteria in phytoremediation of metal-polluted soils: current knowledge and future directions. Sci. Total Environ. 838, 156435.
Arslan, M., Gamal El-Din, M., 2021. Removal of per- and poly-fluoroalkyl substances (PFASs) by wetlands: prospects on plants, microbes and the interplay. Sci. Total Environ. 800, 149570.
Bizkarguenaga, E., Zabaleta, I., Prieto, A., Fernandez, L.A., Zuloaga, O., 2016. Uptake of 8:2 perfluoroalkyl phosphate diester and its degradation products by carrot and lettuce from compost-amended soil. Chemosphere 152, 309–317.
Blaine, A.C., Rich, C.D., Hundal, L.S., Lau, C., Mills, M.A., Harris, K.M., Higgins, C.P., 2013. Uptake of perfluoroalkyl acids into edible crops via land applied biosolids: field and greenhouse studies. Environ. Sci. Technol. 47, 14062–14069.
Blaine, A.C., Rich, C.D., Sedlacko, E.M., Hundal, L.S., Kumar, K., Lau, C., Mills, M.A., Harris, K.M., Higgins, C.P., 2014. Perfluoroalkyl acid distribution in various plant compartments of edible crops grown in biosolids-amended soils. Environ. Sci. Technol. 48, 7858–7865.
Bolan, N., Sarkar, B., Yan, Y., Li, Q., Wijesekara, H., Kannan, K., Tsang, D.C.W., Schauerte, M., Bosch, J., Noll, H., Ok, Y.S., Scheckel, K., Kumpiene, J., Gobindlal, K., Kah, M., Sperry, J., Kirkham, M.B., Wang, H., Tsang, Y.F., Hou, D., Rinklebe, J., 2021a. Remediation of poly- and perfluoroalkyl substances (PFAS) contaminated soils – to mobilize or to immobilize or to degrade? J. Hazard Mater. 401, 123892.
Bolan, N., Sarkar, B., Vithanage, M., Singh, G., Tsang, D.C.W., Mukhopadhyay, R., Ramadass, K., Vinu, A., Sun, Y., Ramanayaka, S., Hoang, S.A., Yan, Y., Li, Y., Rinklebe, J., Li, H., Kirkham, M.B., 2021b. Distribution, behaviour, bioavailability and remediation of poly- and per-fluoroalkyl substances (PFAS) in solid biowastes and biowaste-treated soil. Environ. Int. 155, 106600.
Brusseau, M.L., Anderson, R.H., Guo, B., 2020. PFAS Concentrations in Soils: Background Levels versus Contaminated Sites. Science of the Total Environment, p. 740.
Buck, R.C., Franklin, J., Berger, U., Conder, J.M., Cousins, I.T., De Voogt, P., Jensen, A. A., Kannan, K., Mabury, S.A., Van Leeuwen, S.P., 2011. Perfluoroalkyl and polyfluoroalkyl substances in the environment: terminology, classification, and origins. Integrated Environ. Assess. Manag. 7, 513–541.
Cai, W., Navarro, D.A., Du, J., Ying, G., Yang, B., McLaughlin, M.J., Kookana, R.S., 2022. Increasing ionic strength and valency of cations enhance sorption through hydrophobic interactions of PFAS with soil surfaces. Sci. Total Environ. 817, 152975.
Chen, C.-H., Yang, S.-H., Liu, Y., Jamieson, P., Shan, L., Chu, K.-H., 2019. Accumulation and Phytotoxicity of Perfluorooctanoic Acid and 2, 3, 3, 3-tetrafluoro-2-(hepta-fluoropropoxy) Propanoate in Arabidopsis thaliana and Nicotiana Benthamiana. Environmental Pollution, 113817.
Chen, J., Guo, J., Yang, Z., Yang, J., Dong, H., Wang, H., Wang, Y., Zhan, F., 2023. The application of fertilizer and AMF promotes growth and reduces the cadmium and lead contents of ryegrass (Lolium multiflorum L.) in a copper mining area. Phyton-International Journal of Experimental Botany 92, 471–485.
Collins, C., Fryer, M., Grosso, A., 2006. Plant uptake of non-ionic organic chemicals. Environ. Sci. Technol. 40, 45–52.
Costello, M.C.S., Lee, L.S., 2020. Sources, Fate, and Plant Uptake in Agricultural Systems of Per- and Polyfluoroalkyl Substances. Current Pollution Reports.
Dobrzyński, J., Jakubowska, Z., Dybek, B., 2022. Potential of Bacillus pumilus to directly promote plant growth. Front. Microbiol. 13.
EPA, 2000. Introduction to Phytoremediation. National Risk Management Research Laboratory.
Felizeter, S., McLachlan, M.S., de Voogt, P., 2012. Uptake of perfluorinated alkyl acids by hydroponically grown lettuce (Lactuca sativa). Environ. Sci. Technol. 46, 11735–11743.
Felizeter, S., McLachlan, M.S., De Voogt, P., 2014. Root uptake and trans location of perfluorinated alkyl acids by three hydroponically grown crops. J. Agric. Food Chem. 62, 3334–3342.
Ferrario, C., Peruzzi, C., Cislaghi, A., Polesello, S., Valsecchi, S., Lava, R., Zanon, F., Santovito, G., Barausse, A., Bonato, M., 2022. Assessment of Reed Grasses (Phragmites Australis) Performance in PFAS Removal from Water. A Phytoremediation Pilot Plant Study, Water (Switzerland), p. 14.
Ghisi, R., Vamerali, T., Manzetti, S., 2019. Accumulation of perfluorinated alkyl substances (PFAS) in agricultural plants: a review. Environ. Res. 169, 326–341.
Gobelius, L., Lewis, J., Ahrens, L., 2017. Plant uptake of per- and polyfluoroalkyl substances at a contaminated fire training facility to evaluate the phytoremediation potential of various plant species. Environ. Sci. Technol. 51, 12602–12610.
Gredelj, A., Nicoletto, C., Valsecchi, S., Ferrario, C., Polesello, S., Lava, R., Zanon, F., Barausse, A., Palmeri, L., Guidolin, L., Bonato, M., 2020. Uptake and translocation of perfluoroalkyl acids (PFAA) in red chicory (Cichorium intybus L.) under various treatments with pre-contaminated soil and irrigation water. Sci. Total Environ. 708, 134766.
Haider, F.U., Liqun, C., Coulter, J.A., Cheema, S.A., Wu, J., Zhang, R., Wenjun, M., Farooq, M., 2021. Cadmium toxicity in plants: impacts and remediation strategies. Ecotoxicol. Environ. Saf. 211, 111887.
Hamid, H., Li, L.Y., Grace, J.R., 2018. Review of the fate and transformation of per- and polyfluoroalkyl substances (PFASs) in landfills. Environ. Pollut. 235, 74–84.
Hashem, A., Tabassum, B., Fathi Abd_Allah, E., 2019. Bacillus subtilis: a plant-growth promoting rhizobacterium that also impacts biotic stress. Saudi J. Biol. Sci. 26, 1291–1297.
Higgins, C.P., Luthy, R.G., 2006. Sorption of perfluorinated surfactants on sediments. Environ. Sci. Technol. 40, 7251–7256.
Huff, D.K., Morris, L.A., Sutter, L., Costanza, J., Pennell, K.D., 2020. Accumulation of six PFAS compounds by woody and herbaceous plants: potential for phytoextraction. Int. J. Phytoremediation 22, 1538–1550.
Jankong, P., Visoottiviseth, P., Khokiattiwong, S., 2007. Enhanced phytoremediation of arsenic contaminated land. Chemosphere 68, 1906–1912.
Kavusi, E., Shahi Khalaf Ansar, B., Ebrahimi, S., Sharma, R., Ghoreishi, S.S., Nobaharan, K., Abdoli, S., Dehghanian, Z., Asgari Lajayer, B., Senapathi, V., Price, G. W., Astatkie, T., 2023. Critical review on phytoremediation of polyfluoroalkyl substances from environmental matrices: need for global concern. Environ. Res. 217, 114844.
Krippner, J., Falk, S., Brunn, H., Georgii, S., Schubert, S., Stahl, T., 2015. Accumulation potentials of perfluoroalkyl carboxylic acids (PFCAs) and perfluoroalkyl sulfonic acids (PFSAs) in maize (Zea mays). J. Agric. Food Chem. 63, 3646.
Lechner, M., Knapp, H., 2011. Carryover of perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) from soil to plant and distribution to the different plant compartments studied in cultures of carrots (daucus carota ssp sativus), potatoes (Solanum tuberosum), and cucumbers (cucumis sativus). J. Agric. Food Chem. 59, 11011–11018.
Lesmeister, L., Lange, F.T., Breuer, J., Biegel-Engler, A., Giese, E., Scheurer, M., 2021. Extending the knowledge about PFAS bioaccumulation factors for agricultural plants – a review. Sci. Total Environ. 766, 142640.
Mayakaduwage, S., Ekanayake, A., Kurwadkar, S., Rajapaksha, A.U., Vithanage, M., 2022. Phytoremediation Prospects of Per- and Polyfluoroalkyl Substances: A Review. Environmental Research, p. 212.
Mench, M., Schwitzguebel, J.P., Schroeder, P., Bert, V., Gawronski, S., Gupta, S., 2009. Assessment of successful experiments and limitations of phytotechnologies: contaminant uptake, detoxification and sequestration, and consequences for food safety. Environ. Sci. Pollut. Control Ser. 16, 876–900.
Mench, M., Lepp, N., Bert, V., Schwitzguebel, J.P., Gawronski, S.W., Schroder, P., Vangronsveld, J., 2010. Successes and limitations of phytotechnologies at field scale: outcomes, assessment and outlook from COST Action 859. J. Soils Sediments 10, 1039–1070.
Naidu, R., Nadebaum, P., Fang, C., Cousins, I., Pennell, K., Conder, J., Newell, C.J., Longpré, D., Warner, S., Crosbie, N.D., Surapaneni, A., Bekele, D., Spiese, R., Bradshaw, T., Slee, D., Liu, Y., Qi, F., Mallavarapu, M., Duan, L., McLeod, L., Bowman, M., Richmond, B., Srivastava, P., Chadalavada, S., Umeh, A., Biswas, B., Barclay, A., Simon, J., Nathanail, P., 2020. Per- and Poly-Fluoroalkyl Substances (PFAS): Current Status and Research Needs, vol. 19. Environmental Technology and Innovation.
Nassazzi, W., Lai, F.Y., Ahrens, L., 2022. A novel method for extraction, clean-up and analysis of per- and polyfluoroalkyl substances (PFAS) in different plant matrices using LC-MS/MS. J. Chromatogr., B: Anal. Technol. Biomed. Life Sci. 1212, 123514.
Navarro, I., de la Torre, A., Sanz, P., Porcel, M.A., Pro, J., Carboneb, G., Martinez, M.D., 2017. Uptake of perfluoroalkyl substances and halogenated flame retardants by crop plants grown in biosolids-amended soils. Environ. Res. 152, 199–206.
Nehnevajova, E., Herzig, R., Federer, G., Erismann, K.-H., Schwitzguébel, J.-P., 2005. Screening of sunflower cultivars for metal phytoextraction in a contaminated field prior to mutagenesis. Int. J. Phytoremediation 7, 337.
Nguyen, T.M.H., Bräunig, J., Thompson, K., Thompson, J., Kabiri, S., Navarro, D.A., Kookana, R.S., Grimison, C., Barnes, C.M., Higgins, C.P., McLaughlin, M.J., Mueller, J.F., 2020. Influences of chemical properties, soil properties, and solution pH on soil–water partitioning coefficients of per- and polyfluoroalkyl substances (PFASs). Environ. Sci. Technol. 54, 15883–15892.
Radziemska, M., Gusiatin, Z.M., Cydzik-Kwiatkowska, A., Cerdà, A., Pecina, V., Bęś, A., Datta, R., Majewski, G., Mazur, Z., Dzięcioł, J., Danish, S., Brtnický, M., 2021. Insight into metal immobilization and microbial community structure in soil from a steel disposal dump phytostabilized with composted, pyrolyzed or gasified wastes. Chemosphere 272, 129576.

Rathore, S.S., Shekhawat, K., Dass, A., Kandpal, B.K., Singh, V.K., 2019. Phytoremediation mechanism in Indian mustard (Brassica juncea) and its enhancement through agronomic interventions. Proc. Natl. Acad. Sci. India B Biol. Sci. 89, 419–427.

Sheoran, V., Sheoran, A.S., Poonia, P., 2016. Factors affecting phytoextraction: a review. Pedosphere 26, 148–166.

Stahl, T., Heyn, J., Thiele, H., Huther, J., Failing, K., Georgii, S., Brunn, H., 2009. Carryover of perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) from soil to plants. Arch. Environ. Contam. Toxicol. 57, 289–298.

Stahl, T., Riebe, R.A., Falk, S., Failing, K., Brunn, H., 2013. Long-term lysimeter experiment to investigate the leaching of perfluoroalkyl substances (PFASs) and the carry-over from soil to plants: results of a pilot study. J. Agric. Food Chem. 61, 1784–1793.

Todde, G., Carboni, G., Marras, S., Caria, M., Sirca, C., 2022. Industrial hemp (Cannabis sativa L.) for phytoremediation: energy and environmental life cycle assessment of using contaminated biomass as an energy resource. Sustain. Energy Technol. Assessments 52, 102081.

Vangronsveld, J., Herzig, R., Weyens, N., Boulet, J., Adriaensen, K., Ruttens, A., Thewys, T., Vassilev, A., Meers, E., Nehnevajova, E., Lelie, D., Mench, M., 2009. Phytoremediation of contaminated soils and groundwater: lessons from the field. Environ. Sci. Pollut. Control Ser. 16, 765–794.

Wang, G., Zhang, Q., Du, W., Ai, F., Yin, Y., Ji, R., Guo, H., 2021. Microbial communities in the rhizosphere of different willow genotypes affect phytoremediation potential in Cd contaminated soil. Sci. Total Environ. 769, 145224.

Wen, B., Li, L.F., Liu, Y., Zhang, H.N., Hu, X.Y., Shan, X.Q., Zhang, S.Z., 2013. Mechanistic studies of perfluorooctane sulfonate, perfluorooctanoic acid uptake by maize (Zea mays L. cv. TY2). Plant Soil 370, 345–354.

Wen, B., Li, L.F., Zhang, H.N., Ma, Y.B., Shan, X.Q., Zhang, S.Z., 2014. Field study on the uptake and translocation of perfluoroalkyl acids (PFAAs) by wheat (Triticum aestivum L.) grown in biosolids-amended soils. Environ. Pollut. 184, 547–554.

Xiang, L., Chen, L., Yu, L.Y., Yu, P.F., Zhao, H.M., Mo, C.H., Li, Y.W., Li, H., Cai, Q.Y., Zhou, D.M., Wong, M.H., 2018. Genotypic variation and mechanism in uptake and translocation of perfluorooctanoic acid (PFOA) in lettuce (Lactuca sativa L.) cultivars grown in PFOA-polluted soils. Sci. Total Environ. 636, 999–1008.

Yoo, H., Washington, J.W., Jenkins, T.M., Ellington, J.J., 2011. Quantitative determination of perfluorochemicals and fluorotelomer alcohols in plants from biosolid-amended fields using LC/MS/MS and GC/MS. Environ. Sci. Technol. 45, 7985–7990.

Zhang, W., Liang, Y., 2020. Removal of eight perfluoroalkyl acids from aqueous solutions by aeration and duckweed. Sci. Total Environ. 724, 138357.

Zhang, W., Zhang, D., Zagorevski, D.V., Liang, Y., 2019a. Exposure of Juncus effusus to seven perfluoroalkyl acids: uptake, accumulation and phytotoxicity. Chemosphere 233, 300–308.

Zhang, D., Zhang, W., Liang, Y., 2019b. Distribution of eight perfluoroalkyl acids in plant-soil-water systems and their effect on the soil microbial community. Sci. Total Environ. 697, 134146.

Zhao, H., Qu, B., Guan, Y., Jiang, J., Chen, X., 2016. Influence of salinity and temperature on uptake of perfluorinated carboxylic acids (PFCAs) by hydroponically grown wheat (Triticum aestivum L). SpringerPlus 5, 1–8.

Zhu, J., Wallis, I., Guan, H., Ross, K., Whiley, H., Fallowfield, H., 2022. Juncus sarophorus, a native Australian species, tolerates and accumulates PFOS, PFOA and PFHxS in a glasshouse experiment. Sci. Total Environ. 826, 154184.