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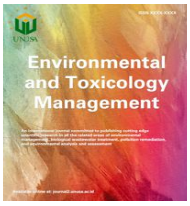

# Phytoremediation of perfluorochemicals: A review of its advances, feasibility and limitations

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## Abstract

The detection of perfluorochemicals (PFCs) in various environmental compartments has raised attention and driven countermeasures to reduce their prevalence. Phytoremediation provides a feasible option for PFCs removal from the environment. Crops such as maize, carrots, lettuce, tomato and spinach have demonstrated the ability to phytoextract and phytoaccumulate PFCs. The bioconcentration factors (BCFs) of PFCs in plants widely vary with plant types, plant parts, the types of PFCs and the properties of soil. Maize straw for instance was shown to have a high BCF (35.23) for perfluorobutanoic acid in comparison to maize kernel with a BCF of only 0.229 for the same compound. Maize leaves have a BCF of 9.39 for perfluorohexane sulphonic acid and maize roots have a BCF of 8.82 for perfluorooctane sulphonic acid. Carrots were found to degrade fluorotelomers whereas silver birch and long beechfern are good accumulators of numerous PFCs. BCFs of perfluoroalkyl carboxylic acids are usually negatively correlated to the carbon chain lengths due to decreasing aqueous solubilities with increasing carbon chain lengths which impede root uptake of the compounds. PCFs phytoremediation is low cost, less energy intensive, operationally simple and environmentally friendly but has the drawbacks of inconsistent performance, long duration, and lacking evidence on mineralization of perfluoroalkyl substances. The use of non-crop plants for PFCs phytoremediation is promulgated due to concern of food wastage and the biomass generated from phytoremediating plants should ideally be suitable as feedstock for bioenergy production. This review contributes to further advancement of PFCs phytoremediation by addressing its current limitations.

Keywords :
Perfluorochemicals, perfluoroalkyl substances, phytoextraction, bioconcentration, perfluoroalkyl carboxylic acids

## 1 Introduction

Perfluorochemicals, perfluorinated compounds (PFCs), refer to a group of synthetic, highly fluorinated, inert organic compounds which have been in use for more than 50 years (Tang and Kristanti, 2022). Their strong carbon-fluorine bonds make them recalcitrant, hence extremely difficult to degrade. This makes them heat- and pH-stable while conferring them hydrophobic and lipophilic properties (Nakayama et al., 2019). Due to these desirable properties, PFCs have found their uses as friction-resistant as well as water- and oil-repelling materials. They are popular in consumer products particularly cookware with non-stick coatings, food packaging, cosmetics, personal care products and easy-to-clean household items. In addition, they are used industrially as textile coatings, leather additives and in metal plating (Phong Vo et al., 2020). Their prevalence in consumer products and industrial applications means that the waste streams from these sources will likely contain PFCs (Lenka et al., 2021). To date, PFCs have become an environmental concern and are classified as emerging pollutants widely found in the environment. Their persistence prolongs their life as well as facilitates their accumulation and spread in the environment (Tang and Kristanti, 2022).

Chemically, PFCs are aliphatic compounds with hydrogens on the carbon chains entirely substituted by fluorine. The fluorocarbon chains may contain different functional groups such as carboxyl and sulphonate groups (Bolan et al., 2021). PFCs with a carboxyl group are called perfluoroalkyl carboxylic acids (PFCAs) while those with a sulfonate group are called perfluoroalkyl sulfonates (Bolan et al., 2021). Within each group, PFCs are named based on the number of carbon atoms in the respective molecules. For instance, perfluorobutanoic acid (PFBA) ($CF_3CF_2CF_2COOH$) contains four carbon atoms and perfluorohexanoic acid ($CF_3CF_2CF_2CF_2CF_2COOH$) contains six carbon atoms. Likewise, perfluorobutane sulfonate ($CF_3CF_2CF_2CF_2HSO_3$) has four carbons (Nganda et al., 2023). PFCs represent a diverse array of chemicals which also include perfluoro sulfates, fluorotelomer alcohols and perfluoro octane sulphuric compounds among others, owing to the various functional groups they are attached to (Nganda et al., 2023).

PFCs are increasingly prevailing in the environment and their persistence crowned them with the name ‘forever chemicals’ (Lenka et al., 2021). They are found in multiple components of the ecosystem. They have been detected in both tap and bottled drinking water from different sources. In the US, perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA) have been reported in community water supplies at 0.4 – 3 ng/L (Andrews and Naidenko, 2020). In China, the drinking water sources in the lower reaches of Yangtze River was found to contain a total PFCAs of 77.49 ng/L (Yu et al., 2022). In Ireland, sampling of bottled water revealed an overall perfluoroalkyl substances (PFASs) concentration of 60 ng/L (Harrad et al., 2019). Besides, PFCs have been detected in wastewater treatment plants. The influent and effluent

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of a wastewater treatment plant in Spain was reported to contain PFBA, perfluoroheptanoic acid (PFHpA) and perfluorohexane sulfonic acid (PFHxS) (Lenka et al., 2021). PFCs have found their ways into food products. PFOS and perfluorodecanoic acid (PFDA) was detected in canned tuna in water at 76 ng/kg and 72 ng/kg respectively (Genualdi et al., 2022). Protein powder concentrate and liquid milk are not spared from PFCs, particularly PFOS and PFCAs (Fujii et al., 2012; Genualdi et al., 2022; Park et al., 2021).

PFCs are known to leach into the environment from landfills, industrial parks, wastewater treatment plants and firefighting training grounds, resulting in significant and widespread soil and water pollution (Stoiber et al., 2020). Studies have revealed the presence of PFCs in the soils globally, indicating soil as a reservoir of PFCs (Brusseau et al., 2020; Stoiber et al., 2020). PFCs in soil originate from multiple sources and these sources could be largely classified as primary sources such as fire-training grounds and fluorochemical plants which directly emit PFCs into the soil, as well as secondary sources such as biosolids and irrigation water which transfer PFCs from the primary sources to soil (Brusseau et al., 2020). PFCs are also present in soil without an apparent source in its proximity and in the remote regions, thus, implying the atmospheric transport of PFCs (Muir et al., 2019). In certain instances, the versatile uses of PFCs such as in ski waxes, led to their elevated concentrations in remote skiing areas (Grønnestad et al., 2019). Nonetheless, PFCs in contaminated sites are often significantly higher than sites without apparent PFCs sources. PFOS of hundreds of mg/kg have been detected at contaminated sites and total PFCs as high as 43261 ng/g was reported in New York, US (Zhang et al., 2020). Wang et al. (2018) found PFOA to be present in the natural forested mountain sites of China in the range of <0.9 to 9.0 pg/g.

The ubiquity of PFCs has prompted investigations into their removal from the environment. Bioremediation has come into the limelight due to its relatively environmentally friendly approach without the need for strong chemicals and intensive energy consumption, unlike technologies such as photocatalysis, electrochemical oxidation, adsorption and plasma technology which have also been proposed as options for PFCs removal (Saleem et al., 2020; Hou et al., 2022). Besides, these technologies also incur high operational cost and generate waste which mandates careful disposal (Hou et al., 2022). Microorganisms such as bacteria and fungi with ability to degrade C-F bonds are the candidates for bioremediation but their effectiveness in biodegrading PFCs is frequently limited due to the strong C-F bonds (Liong et al., 2021; Tang and Hadibarata, 2022). With soil being a major reservoir of PFCs, phytoremediation offers a seemingly workable option to remove PFCs from a large tract of contaminated land. To the best author knowledge, there is no review which discuss on phytoremediation technique for reducing PFCs in soil. Thus, this review aims to examine if phytoremediation is a feasible option for reducing PFCs in soil and the limitations of this strategy. It has been conducted through Google Scholar databases as part of the traditional literature review method used in this study. The collected articles were analyzed, summarized, synthesized, and insights were derived from the articles using the narrative synthesis method.

## 2 Advances in the phytoremediation of PFCs

Phytoremediation involves the use of plants to remove contaminants from an environmental medium. Soil and water are the most common environmental media where phytoremediation is employed, though plants have also been used to purify air (Tang, 2019a). Phytoremediation can be achieved through numerous mechanisms consisting of phytostabilization, phytoaccumulation, phytoextraction, rhizofiltration, phytodegradation, rhizodegradation and phytovolatilization (Tang et al., 2020). In short, phytostabilization is accomplished through the sequestration of contaminants on plant roots or in the rhizosphere through root secretion or plant-microbe interactions (Tang and Angela, 2019). Phytoextraction involves the uptake of contaminants by plant roots and their subsequent translocation, accumulation or metabolism. Once taken up by plants through roots, the contaminants can be transported to different parts of the plants where accumulation occurs, often without degradation, leading to phytoaccumulation (Tang, 2021). Rhizofiltration is similar to phytoextraction and focuses on the use of well-developed and acclimated plant root system to remediate contaminated water through root uptake (Tang et al., 2020). Phytodegradation uses plant enzymes to degrade contaminants fully or partially, and this usually takes place within plants. Like phytodegradation, rhizodegradation also involves the mineralization or partial degradation of contaminants through the symbiotic relationship between plants and rhizosphere-dwelling microorganisms where plant roots provide the microbes with nutrients to enhance biodegradation (Tang and Law, 2019). During phytovolatilization, contaminants are removed through evaporation or volatilization from leaf surfaces (Tang and Chai, 2020).

In the case of PFCs, the common mechanisms reported involve phytoextraction or rhizofiltration, phytodegradation and phytoaccumulation. Plants have demonstrated the ability to absorb and accumulate PFCs with long-chain PFCs accumulated to a higher extent in roots while short chains in buds, fruits and crops (Li et al., 2019). Most of the recent studies related to phytoremediation of PFCs were conducted on crops. Maize (Zea Mays) has been extensively studied and it was found that different parts of maize have different ability to bioaccumulate PFCs. In a study, maize straw was reported to have a bioconcentration factor (BCF) of 35.23 for PFBA and 1.84 for perfluorobutane sulphonic acid (PFBS), in contrast to maize kernel with BCFs of 0.229 and 0.005 for PFBA and PFBS respectively (Table 1) (Krippner et al., 2015). Another study revealed that maize leaves have a BCF of 9.59 for PFHxS and 4 for PFBS whereas maize roots have a BCF of 2.62 for PFHxS and 5 for PFBS (Table 1) (Navarro et al., 2017). The studies indicate that different maize parts have different BCFs even for the same chemicals, such as PFBS. It is likely that BCFs of a similar plant part differ in different studies due to the presence of numerous factors influencing BCFs, for instance the properties of soil, availability of water, humidity and temperature, which potentially affect the availability of PFCs and evapotranspiration hence the uptake of PFCs by plants (Li et al., 2019).

Furthermore, carrots of Chantenay variety were shown to be able to accumulate and degrade 8:2 fluorotelomer phosphate diester (8:2 diPAP) through the detection of 8:2 diPAP in their peels (total BCF = 0.025 – 0.037) and its breakdown products comprising perfluorononanoic acid (PFNA), PFOA, PFHpA, perfluorohexanoic acid (PFHxA), perfluoropentanoic acid (PFPeA) and PFBA. The lower BCF of 8:2 diPAP was likely attributed to its relatively higher biodegradability. The degradation products have different total BCFs in carrot tissues with PFBA having a BCF ranging from 23.3 to 33 (Bizkarguenaga et al., 2016). It was not reported if the degradation products further broke down and it seems that degradation products such as PFHxA, PFPeA and PFBA were accumulated to significant extents. A correlation was tracked between BCFs of PFCAs and the carbon chain lengths, where longer chain lengths were linked to lower BCFs. This was probably because of decreased aqueous solubility of PFCAs as carbon chain lengths increase, which limits the uptake of longer PFCAs by carrot roots (Bizkarguenaga et al., 2016). In the same study, biodegradation of 8:2 diPAP by lettuce only yielded PFOA and accumulation of both PFCs was only significantly observed in the hearts of the plant (BCF = 0.0025 – 0.0068 for 8:2 diPAP and BCF = 0.089 – 0.093 for PFOA), implying a lack of translocation unlike in carrots where translocation to the leaves occurred (Table 1) (Bizkarguenaga et al., 2016).

PFCs were found to accumulate in tomato fruits where the total amount of PFASs was concentrated 7.84 times higher in the fruit tissues than the soil. PFBA bioconcentration (BCF = 16.8) was particularly remarkable (Table 1). The same was observed for spinach with PFBA having a BCF of 12.47 and PFOS 4.63 (Navarro et al., 2017). In tomato fruits, PFBA had a significantly higher BCF than PFOA probably because of its substantially higher aqueous solubility and lower hydrophobicity which facilitated its uptake by the plant. This is in line with the findings of Bizkarguenaga et al. (2016) highlighting a negative correlation between BCFs and carbon chain lengths of PCFs. Gobelius et al. (2017) documented seven plants with varying capacity of extracting and accumulating PFCs (Table 1). It is noteworthy that silver birch could significantly (BCF > 10) bioconcentrate PFNA, PFDA, PFBS, linear and branched PFOS and 6:2 fluorotelomer sulfonic acid (6:2 FTSA). Its ability to extract and accumulate 6:2 FTSA was outstanding with BCFs up to 13698 (see Table 1 for the respective BCFs). Norway spruce was a good accumulator (BCF > 10) of PFBA, PFHxA, PFOA, PFBS, linear PFHxS, branched PFOS and 6:2 FTSA, especially PFBA with BCF reaching 98. Mountain ash could significantly bioconcentrate PFPeA (BCF = 0.56 – 2737), PFHpA (BCF = 0.15 – 98), linear and branched PFHxS and 6:2 FTSA while long beenchfern bioconcentrated PFPeA, PFHpA, PFOA, PFBS, linear and branched PFHxS as well as linear and branched PFOS to good extents (BCF ≥15) (Table 1). Long beachfern was particularly remarkable in phytoextracting PFPeA and PFHpA with BCFs of 5450 and 175 respectively (Table 1) (Gobelius et al., 2017).

A sedge by the scientific name Juncellus serotinus is a wetland plant with phytoremediation potential. While its ability to remove PFCs from soil has not been documented, a study demonstrated its ability to extract and concentrate PFCs particularly PFBA, PFPeA, PFHxA, perfluoroundecanoic acid (PFUnDA),PFHxS and PFOS from surface water with BCFs between 4 to 5.5. Again, a negative correlation has been noted between BCF and carbon chain length of PFCAs, except for PFUnDA in this instance (Wang et al., 2019). The BCFs of perfluoroalkyl sulfonates were also determined by their respective aqueous solubilities which do not seem to decrease with carbon chain lengths (Table 1). PFHxS, for example has an aqueous solubility of 7.59 while PFOS has an aqueous solubility of 0.21 (Nganda et al., 2023). A recent study shows red chicory to be a good candidate for phytoremediating PFCs, namely PFBA, PFPeA, PFHxA, PFHpA and PFBS with BCF > 10 in either the roots or heads of the plant. The study also points to different accumulation of PFCs in different plant parts with roots having higher BCFs than heads (Gredelj et al., 2020).

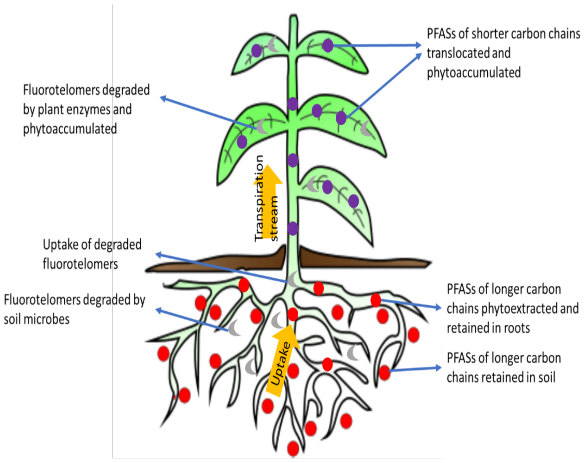

**Figure 1** Mechanisms of PFCs phytoremediation

**Table 1** Exposure parameters to assess the health risks of the study population caused by As

| Plant | Treatment Duration | Concentration in Plant Tissues (ng/g dW) | Bioconcentration Factor (BCF) | Reference |
|---|---|---|---|---|
| Maize (Zea mays) straw | 128 days | PFBA: 35233<br>PFBS: 1843<br>PFOA: 645<br>PFOS: 617<br>PFASs = 52200 | PFBA (35.23)<br>PFBS (1.84)<br>PFOA (0.65)<br>PFOS (0.62) | Krippner et al., 2015 |
| Maize (Zea mays) kernels | 128 days | PFBA: 229<br>PFBS: 5.44<br>PFOA: 2.45<br>PFOS: <LOQ PFASs = 860 | PFBA (0.229)<br>PFBS (0.005)<br>PFOA (0.002) | Krippner et al., 2015 |
| Carrots (Daucus carota) (Chantenay variety) | Approx. 3 months | 8:2 diPAP: 4.9 – 6.6 (peel); 5.5 – 7.8 (leaves)<br>PFNA: 1.1 (peel); 1.1 – 1.2 (leaves)<br>PFOA: 70 (peel); 93 – 157 (leaves)<br>PFHpA: 5-7 (peel); 18-21 (leaves)<br>PFHxA: 10.2-20 (peel); 102-144 (leaves)<br>PFPeA: 8.7-20 (peel); 93-115 (leaves)<br>PFBA: 28-15 (peel); 116-130 (leaves) | 8:2 diPAP (0.025-0.037)<br>PFNA (0.74)<br>PFOA (0.86-1.43)<br>PFHpA (0.64-1.23)<br>PFHxA (4.6-11)<br>PFPeA (8.0-12.4)<br>PFBA (23.3-33) | Bizkarguenaga et al., 2016 |
| Lettuce (Lactuca sativa) (Batavia Golden Spring variety) | Approx. 1 month | 8:2 diPAP: 11-17 (heart)<br>PFOA: 15-26 (heart) | 8:2 diPAP (0.0025-0.0068) PFOA (0.089-0.093) | Bizkarguenaga et al., 2016 |
| Maize (Zea mays) | leaves 28 days | PFOS: 23100<br>PFBS: 120<br>PFHxS: 7980 | PFOS (0.80)<br>PFBS (4)<br>PFHxS (9.39) | Navarro et al., 2017 |
| Maize (Zea mays) roots | 28 days | PFOS: 254000<br>PFBS: 150<br>PFHxS: 2230 | PFOS (8.82)<br>PFBS (5)<br>PFHxS (2.62) | Navarro et al., 2017) |

| Plant | Treatment Duration | Concentration in Plant Tissues (ng/g dW) | Bioconcentration Factor (BCF) | Reference |
|---|---|---|---|---|
| Tomato (Solanum lycopersicum L.) fruits | 6 months | PFBA: 12.45<br>PFOA: 0.18<br>PFOS: 0.03<br>$\sum PFASs = 61.3$ | PFBA (16.8)<br>PFOA (0.15)<br>PFOS (0.06)<br>$\sum PFASs (7.84)$ | Navarro et al., 2017 |
| Spinach (Spinacia oleracea) | 28 days | PFOA: 2.37<br>PFOS: 1.62<br>$\sum PFASs = 61.3$ | PFOA (12.47)<br>PFOS (4.63)<br>$\sum PFASs = 3.70$ | Navarro et al., 2017 |
| Silver birch (Betula pendula) | Not specified | $\sum PFCAs : ND - 828$<br>$\sum PFSAs : 0.26 - 295$<br>$\sum FTSAs/FOSAs/FOSEs/FOSAAs : 0.13 - 1594$ | PFOA (0.007-5.1)<br>PFNA (0.12-35)<br>PFDA (25)<br>PFBS (0.0206-13)<br>PFHxS linear (0.0028-8.8)<br>PFOS linear (0.00032-11)<br>PFOS branched (0.00029-12)<br>6:2 FTSA (0.034-13698) | Gobelius et al., 2017 |
| Norway spruce (Picea podagraria) | Not specified | $\sum PFCAs : ND - 117$<br>$\sum PFSAs : 0.54 - 59$<br>$\sum FTSAs/FOSAs/FOSEs/FOSAAs : 0.83 - 45$ | PFBA (5.3-98)<br>PFPeA (1.8-5.6)<br>PFHxA (0.49-54)<br>PFHpA (0.16-6.7)<br>PFOA (1.5-41)<br>PFNA (5.5)<br>PFBS (0.49-11)<br>PFHxS linear (0.11-56)<br>PFOS linear (0.011-6.0)<br>PFOS branched (0.0083-11)<br>6:2 FTSA (0.12-68) | Gobelius et al., 2017 |
| Bird cherry (Prunus padus) | Not specified | $\sum PFCAs : ND - 7.5$<br>$\sum PFSAs : ND - 1.1$<br>$\sum FTSAs/FOSAs/FOSEs/FOSAAs : 0.30 - 4.3$ | PFBA (8)<br>PFBS (0-7)<br>PFHxS linear (0-3)<br>6:2 FTSA (12-609) | Gobelius et al., 2017 |
| Mountain ash (Sorbus aucuparia) | Not specified | $\sum PFCAs : 0.039 - 7.4$<br>$\sum PFSAs : 0.26 - 13$<br>$\sum FTSAs/FOSAs/FOSEs/FOSAAs : 0.22 - 44$ | PFPeA (0.56-2737)<br>PFHpA (0.15-98)<br>PFDA (0.72-6.1)<br>PFHxS linear (0.26-39)<br>PFHxS branched (10)<br>6:2 FTSA (5-223) | Gobelius et al., 2017 |
| Ground elder (Aegopodium podagradia) | Not specified | $\sum PFCAs : ND - 0.51$<br>$\sum PFSAs : 0.65 - 2.7$<br>$\sum FTSAs/FOSAs/FOSEs/FOSAAs : 1.4 - 80$ | PFBS (2.2-182)<br>6:2 FTSA (16-3983) | Gobelius et al., 2017 |
| Long beechfern (Phegopteris connectilis) | Not specified | $\sum PFCAs : 0.067 - 34$<br>$\sum PFSAs : 1.7 - 3.0$<br>$\sum FTSAs/FOSAs/FOSEs/FOSAAs : ND$ | PFPeA (5450)<br>PFHpA (175)<br>PFOA (26)<br>PFBS (52)<br>PFHxS linear (129-140)<br>PFHxS branched (15)<br>PFOS linear (82-906)<br>PFOS branched (39-131) | Gobelius et al., 2017 |
| Wild strawberry (Fragaria vesca) | Not specified | $\sum PFCAs : 4.2 - 5.0$<br>$\sum PFSAs : ND - 0.14$<br>$\sum FTSAs/FOSAs/FOSEs/FOSAAs : 0.85 - 3.7$ | PFPeA (3.2)<br>6:2 FTSA (32) | Gobelius et al., 2017 |

| Plant | Treatment Duration | Concentration in Plant Tissues (ng/g dW) | Bioconcentration Factor (BCF) | Reference |
|---|---|---|---|---|
| Sedge (Juncellus serotinus) | Naturally occurring | PFBA: 12.2<br>PFPeA: 0.30<br>PFHxA: 0.94<br>PFHpA: 0.02<br>PFOA: 0.98<br>PFUnDA: 0.20<br>PFBS: 1.44<br>PFHxS: 0.29<br>PFOS: 1.07 | PFBA (4.34)<br>PFPeA (4.23)<br>PFHxA (4.62)<br>PFHpA (2.90)<br>PFOA (2.82)<br>PFUnDA (5.24)<br>PFBS (3.85)<br>PFHxS (5.45)<br>PFOS (4.19) | Wang et al., 2019 |
| Red chicory (Cichorium intybus L.) | 87 days (from transplanting) | PFBA: 40037.3 (roots); 9835.8 (heads)<br>PFPeA: 18150.5 (roots); 5345 (heads)<br>PFHxA: 7443.7 (roots); 4757.4 (heads)<br>PFHpA: 3373.8 (roots); 2139 (heads)<br>PFOA: 1714.9 (roots); 1075.9 (heads)<br>PFNA: 850.3 (roots); 538.6 (heads)<br>PFDA: 728.4 (roots); 459.2 (heads)<br>PFBS: 19125.8 (roots); 12201.5 (heads)<br>PFOS: 1064.2 (roots); 672.32 (heads) | PFBA (roots = 179.9; heads = 44.2)<br>PFPeA (roots = 79.0; heads = 23.3)<br>PFHxA (roots = 30.0; heads = 19.2)<br>PFHpA (roots = 12.4; heads = 7.8)<br>PFOA (roots = 7.2; heads = 4.5)<br>PFNA (roots = 3.2; heads = 2.0)<br>PFDA (roots = 2.7; heads = 1.7)<br>PFBS (roots = 71.8; heads = 45.8)<br>PFOS (roots = 3.6; heads = 2.3) | Gredelj et al., 2020 |

Note: Bioconcentration Factor (BCF) = Ratio of concentration in plant tissue to concentration in substrate (soil); LOQ = Limit of quantification; ND = Not detected; FOSA = perfluorooctane sulfonamide; FOSE = perfluorooctane sulfonamidoethanol; FOSAA = fluorooctane sulfonamide acetic acid

In the studies reviewed, phytoextraction and phytoaccumulation of PFCs in plants are most apparent except in a study highlighting phytodegradation of 8:2 diPAP (Bizkarguenaga et al., 2016). This indicates that fluorotelomers are generally more readily biodegraded either in soil or in plants into the respective PFASs. However, it remains unclear if the PFASs undergo further phytodegradation and therefore, presents a dimension with much potential for further investigation. Rhizofiltration was reported in sedge mainly because the study was conducted on contaminated surface water and it is a variant of phytoextraction, implying phytoextraction through solubilization of PFCs and root uptake was an important mechanism for PFCs phytoremediation (Wang et al., 2019). Another study of rhizofiltration was conducted with three hydroponically grown willow species (*Salix eleagnos* L., *Salix purpurea* L. and *Salix triandra* L.) which showed that the willow species could remove 6 to 11% of total PFCAs (S. purpurea = 11%; S. eleagnos = 9%; S. triandra = 6%). S. eleagnos leaves contained significantly higher PFNA and PFOS than those of *S. purpurea* while *S. purpurea* roots contained higher PFHxA, PFHpA and PFBS than those of other willow species. The study revealed that longer chain PFCAs tended to accumulate in the roots and the opposite was observed for perfluoroalkyl sulfonates with leaves containing high PFOS and low PFBS (Sharma et al., 2020).

# 3 Feasibility of PFCs phytoremediation

Phytoremediation of PFCs offers the advantage of simplicity in comparison with other remediation strategies. A wide range of crops or plants is available to clean up different types of PFCs from different types of soil, though at different efficiencies (Gobelius et al., 2017). PFCs with high aqueous solubilities tend to be more readily taken up by plants and translocated to other plant parts while those with lower aqueous solubilities, such as PFCAs of longer carbon chains are more likely to retain in the roots, if not adsorbed by soil particles (Bizkarguenaga et al., 2016; Sharma et al., 2020). While soils of different properties such as the contents of organic and inorganic matter are known to affect BCFs of phytoremediating plants, no special soil treatment is required for the plants to carry out phytoremediation unlike chemical treatments which often require the use of redox reagents or soil washing agents to degrade or scrub PFCs from contaminated soil and in the process, produce other pollutants or wastewater needing separate treatment (Kucharzyk et al., 2017). In this regard, phytoremediation offers a relatively cleaner and environmentally friendly way of removing PFCs.

Adsorption of PFCs with adsorbents such as granular activated carbon is an established method of remediating soil contaminated with PFCs but the used adsorbents require special treatments such as thermal destruction to destroy the adsorbed PFCs (Park et al., 2020). Phytoremediation may have a similar limitation of retaining the contaminants in crop which will be discussed subsequently. It is also likely that phytodegradation and rhizodegradation of PFCs especially fluorotelomers would occur, thus reducing the contaminant loads (Bizkarguenaga et al., 2016). Besides, root-microbe interactions in the rhizosphere might facilitate breakdown of PFCs, further reducing contaminant loads (Tang and Kristanti, 2022). Besides, phytoremediation has low energy requirement in comparison to methods such as photocatalysis, electrochemical oxidation, sonochemical and thermolysis treatment that frequently require high energy input and indirectly contribute to greenhouse gas emissions (Kucharzyk et al., 2017). In fact, phytoremediation offers a co-benefit of acting as a sink for greenhouse gases, thus, may indirectly contribute to the mitigation of climate change (Tang, 2019b). In addition, phytoremediation has an obvious advantage of low cost because it does not require specialized chemical reagents and expensive equipment. It also offers greening advantage while plants act to reduce the bioavailability of PFCs through immobilization and root sorption (Gredelj et al., 2020).

## 4 Limitations of PFCs phytoremediation

While phytoremediation is a feasible option for PFCs removal, it has certain limitations that require attention. Phytoremediation is a time-consuming process and may limit the land use of a contaminated land. It may therefore not be appropriate when the timeframe for remediation is short due to urgent development (Gobelius et al., 2017; Bolan et al., 2021). The effectiveness of phytoremediation varies widely depending on the plants used. Some plants are more effective in removing certain PFCs than the other and careful selection of plants is important to optimize effectiveness (Table 1) (Li et al., 2019). Even with optimization, complete removal of PFCs (see Table 1) is rarely achieved and in some instances, removal of PFCs to regulatory permissible levels could also be challenging (Tang and Kristanti, 2022). While plants are known to break down fluorotelomers, it is uncertain if the resultant PFASs are further degraded, and this is rarely reported. It is therefore likely that plants might retain the bulk of PFASs in their tissues due to the strong C-F bonds unfavorable for biodegradation and return the PFASs to the soil with their natural shedding (Bizkarguenaga et al., 2016; Nganda et al., 2023). With the uncertainty in the fates of PFASs in plants, phytoremediation may generate a large amount of biomass which requires special treatment such as incineration, thus not endowing it much advantage over the use of adsorbents or bio-adsorbents. Most of the existing phytoremediation studies have been conducted with crops which may raise the concern of sustainability since the crops may not be fit for consumption after phytoremediation and may need to be disposed of, causing wastage. Plants are not effective in removing PFCs of low aqueous solubilities and these contaminants could remain sorbed to soil particles.

## 5 Conclusion

Phytoremediation provides an exciting alternative to remove PFCs from the environment which are notorious for being persistent and ubiquitous. Different plants, particularly crops have been shown to remove different PFCs and they are accumulated at different BCFs in different plant parts. Phytoremediation has the advantages of low cost, uncomplicated, environmentally friendly and not energy intensive. However, it also has certain limitations, such as inconsistent performances, uncertainty in PFASs breakdown and generation of voluminous contaminated biomass, that need to be overcome. This review is significant in accentuating the advances in phytoremediation of PFCs to realistically present its feasibility and limitations. It opines that more studies related to the fates of PFCs in phytoremediating plants are essential to understand if PFCs are biodegraded or mineralized. It promulgates the co-application of phytoremediation and bioremediation to enhance the plant-microbe interactions in breaking down PFCs. It suggests a careful planning of phytoremediation regime as a part of greening plan to allow plants to clean up PFCs-contaminated soil without the pressure of redevelopment. Besides, it is suggested to use non-crop plants for phytoremediation to minimize potential sustainability controversy and to use plants suitable for bioenergy generation. Having said that, the biomass generated from phytoremediation could be used as feedstock for energy production where appropriate.

## Declaration of competing interest

The authors declare no known competing interests that could have influenced the work reported in this paper.

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