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REVIEW ARTICLE

Review on plant uptake of PFOS and PFOA for environmental cleanup: potential and implications

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Abstract

Perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) have gained increasing concern due to their persistent characteristics, wide distribution, biotoxicity, and bioaccumulative properties. The current remediation technologies for PFOA and PFOS are primarily focused on physical and chemical techniques. Phytoremediation has provided promising alternatives to traditional cleanup technologies due to their low operational costs, low maintenance requirements, end-use value, and aesthetic nature. In this review, uptake, translocation, and toxic effects of PFOS and PFOA are summarized and discussed. Several potential hyperaccumulators of PFOS and PFOA are provided according to the existing data. Biomass, chlorophyll, soluble protein, enzyme activities, oxidative stress, and other variables are assessed for potential indicator of PFOS/PFOA biotoxicity. The various studies on multiple scales are compared for identifying the threshold values. Several important implications and recommendations for future research are proposed at the end. This review provides an overview of current studies on plant uptake of PFOS and PFOA from the perspective of phytoremediation.

Keywords PFOA · PFOS · Plant uptake · Translocation · Bioaccumulation

Introduction

Per- and polyfluoroalkyl substances (PFASs) are well known as anthropogenic chemicals applied in a wide range of practical applications for over 60 years (Lindstrom et al. 2011; Xiao 2017). These uses of PFASs have caused a ubiquitous distribution in seawater (Su et al. 2018), municipal wastewater (Gallen et al. 2018; Wang et al. 2016), surface water (Cai et al. 2018; Houtz and Sedlak 2012; Liu et al. 2015; Liu et al. 2017), underground water (Braunig et al. 2017; Liu et al. 2017; Martin et al. 2019), soil (Choi et al. 2017; Rankin et al. 2016; Sun et al. 2017), forests (Dasu et al. 2013), and air (Ahrens et al. 2012; Ahrens et al. 2011; Vierke et al. 2013). Perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) are highlighted as the most studied and frequently detected PFASs in various environmental matrices (Mudumbi et al. 2017; Newton et al. 2017; Wang et al. 2017b). Because of their strong carbon-fluorine (C-F bonds) (3.6 eV, 116 kcal/mol) (Kim et al. 2019) and the multiple C-F bonds in close proximity, the decomposition of PFOA and PFOS is extremely difficult. It is evident that the widespread distribution and persistence of PFOA and PFOS (Du et al. 2014; Zareitalabad et al. 2013) have provided the opportunity for bioaccumulation in various plants (Blaine et al. 2014a; Blaine et al. 2014b; Felizeter et al. 2014; Zabaleta et al. 2018) and animals (Ahrens and Bundschuh 2014; Chen et al. 2018; Dorneles et al. 2008; Houde et al. 2008). The bioaccumulation of PFASs has produced toxic effects in human bodies (Coakley et al. 2018; Jusko et al. 2016; Salgado-Freiria et al. 2018). Bioaccumulation of PFOA and PFOS in human bodies could be attributed to food and/or drinking water (Zeng et al. 2019); therefore, techniques

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to eliminate the trace PFOA and PFOS contamination in the aqueous environment and soils have become urgent.

Scientific methods to remove PFOA and PFOS from aqueous solution and soil by using physical and chemical techniques have included adsorption (Du et al. 2016; Fagbayigbo et al. 2017; Park et al. 2018), coagulation (Bao et al. 2014), reverse osmosis (Tang et al. 2006), thermal treatment (Wang et al. 2013), sonolysis (Cheng et al. 2008, 2010), electron beam (Kim et al. 2018), photocatalysis (Wang et al. 2017a), advanced oxidation/reduction (Trojanowicz et al. 2018), and phytoremediation (Gobelius 2016). The majority of previous studies focused on physical and chemical techniques due to the biorefractory properties of PFOA and PFOS, and these physical and chemical techniques are efficient and economically feasible in high concentrations of PFOA and PFOS in water or soil. In terms of trace concentrations in natural environments, extremely high costs (Nzeribe et al. 2019) and inhibitions of coexisting chemicals (e.g., inorganic ions and humic acids) (Sun et al. 2019) have become the obstacles of full-scale application of physical and chemical techniques. In this case, plant-based remediation (i.e., phytoremediation) could provide an economic and non-inhibitory alternative for PFOA and PFOS removal. Plants have developed strategies to take up chemicals present in soil and aqueous environments (Lan et al. 2018; Pullagurala et al. 2018; Zhang et al. 2016). And phytoremediation has been confirmed as an effective technique in various fields (Dhir 2013; Pullagurala et al. 2018). PFOA and PFOS removal using plant-based remediation is a strategy due to its low cost and broad adaptability, and this technique could act as a supplementary method or process for future physical and chemical techniques.

The selection of plant species for efficient uptake of PFOA and PFOS is critically important for developing successful phytoremediation; therefore, the uptake, translocation, and distribution of these substances in different plants are summarized and discussed. Although there are some studies focusing on the PFAS uptake by agricultural plants (Ghisi et al. 2019), their objectives are mainly connected with food security rather than environmental cleanup. In this study, two parameters, bioconcentration factors (based on root uptake) and translocation factors, are frequently employed to reflect the bioaccumulation ability and transferring property, respectively (Mudumbi et al. 2014; Pi et al. 2017; Zhang et al. 2019). BCF(Log) was introduced to demonstrate the differences in ability of accumulation among plant species clearly. In addition, the toxic effects of PFOS and PFOA on plants are summarized to provide a reference for practical limitations. The aim of this review is to summarize uptake and translocation of PFOA and PFOS by various plant species and analyze the toxic influences of PFOA and PFOS on plants. Implications for future research are provided at the end based on the existing studies and the knowledge of authors.

$$\mathrm{BCF} = C_{\mathrm{plant}}/C_{\mathrm{environment}}. \quad (1)$$

The ratio of PFOA/PFOS concentration observed in the plant and matrix:

$$\mathrm{TF} = C_{\mathrm{tissue2}}/C_{\mathrm{tissue1}}. \quad (2)$$

The ratio of the chemical concentration measured in different tissues of plant:

$$\mathrm{BCF(Log)} = \mathrm{Log}_{10}^{\mathrm{BCF}}. \quad (3)$$

Uptake of PFOS and PFOA by different plant species

Aquatic and wetland plants

Aquatic and wetland plants have been considered as potential plants for PFOS and PFOA uptake from wastewater in the past decade (Table 1). To demonstrate clearly the potential of various plant species for PFOS and PFOA uptake, the BCFs of existing plants were compared with a reference line of average value. In these investigations, plant species were subjected to certain concentrations of PFOS and/or PFOA in wetlands or lab conditions, and various tissues of selected plants were sampled, tested, and calculated for further analysis. According to Fig. 1, it was obvious that the average BCF(Log) of PFOS (2.358) was significantly higher than that of PFOA (0.048). The relative BCF(Log) level of plants could be used to scientifically test potential hyperaccumulators. In addition, several plant species were found capable of taking both PFOS and PFOA from matrixes (including water and soil) (Wilkinson et al. 2018). An investigation on spatial accumulation of organic contaminants, including perfluorinated compounds in river sediment, aquatic plants, and benthic organisms was conducted from several selected river catchments in the UK (Wilkinson et al. 2018). It was found that the starwort *Callitriche* sp. (*Callitriche stagnalis* Scop) and the pondweed *Potamogeton* sp. (*Potamogeton distinctus* A. Bennett) showed outstanding uptake of both PFOS and PFOA in natural environments (Wilkinson et al. 2018). Other plant species presented efficient uptake of PFOS or PFOA solely (Fig. 1) (Chen et al. 2012; Zhang et al. 2019). In a pilot study, 90 L of a solution containing a concentration of 5 mg/L of PFOA and PFOS was prepared and poured into each pilot tank to simulate the wastewater treatment (Chen et al. 2012). 0.77%~1.58% PFOA and 3.64%~6.05% PFOS were absorbed by the selected four plants (*Hygrophila pogonocalyx* Hayata, *Ipomoea aquatica* Forssk, *Ludwigia* × *taiwanensis* C. I. Peng, and *Eleocharis dulcis* Burm, f. Trin. Ex Hensch) at the end of the 15-day experiment (Chen et al. 2012). Though higher BCF(Log) values were observed for PFOS in all of the four plants, those of PFOA were notably higher than the average value of previous studies (Fig. 1), indicating the four plants

Table 1 The summary of existing PFOS and PFOA uptake in aquatic and wetland plants

Plant	PFASs	Scale	Calculation matrix	Exposure time	BCF(Log)	Ref.
H. pogonocalyx (*Hygrophila pogonocalyx* Hayata)	PFOA	Pilot	Water	15 d	1.11	Chen et al. 2012
Water spinach (*Ipomoea aquatic* Forssk)	PFOA	Pilot	Water	15 d	0.95	Chen et al. 2012
L. (x) *taiwanensis* (*Ludwigia* × *taiwanensis* C. I. Peng)	PFOA	Pilot	Water	15 d	0.90	Chen et al. 2012
Water chestnut (*Eleocharis dulcis* Burm)	PFOA	Pilot	Water	15 d	0.69	Chen et al. 2012
H. pogonocalyx (*Hygrophila pogonocalyx* Hayata)	PFOS	Pilot	Water	15 d	2.26	Chen et al. 2012
Water spinach (*Ipomoea aquatic* Forssk)	PFOS	Pilot	Water	15 d	1.93	Chen et al. 2012
L. (x) *taiwanensis* (*Ludwigia* (x) *taiwanensis* C. I. Peng)	PFOS	Pilot	Water	15 d	1.90	Chen et al. 2012
Water chestnut (*Eleocharis dulcis* Burm)	PFOS	Pilot	Water	15 d	1.85	Chen et al. 2012
Cocklebur (*Xanthium strumarium* L)	PFOA	Full	Sediment	–	−1.17	Mudumbi et al. 2014
Reed (*Phragmites australis* (Cav.) Trin)	PFOA	Full	Sediment	–	−1.28	Mudumbi et al. 2014
Widgeon grass (*Ruppia maritima L*)	PFOA	Full	Sediment	–	−1.32	Mudumbi et al. 2014
S. corymbosus (*Schoenoplectus corymbosus* (Roth ex Roem. & Schult.) J. Raynal)	PFOA	Full	Sediment	–	−1.34	Mudumbi et al. 2014
P. salicifolium (*Polygonum salicifolium* (Mattf.))	PFOA	Full	Sediment	–	−0.74	Mudumbi et al. 2014
C. congestus (*Cyperus congestus* Vahl)	PFOA	Full	Sediment	–	−0.84	Mudumbi et al. 2014
P. x *canescens* (*Populus canescens* (Ait.) Smith)	PFOA	Full	Sediment	–	−0.85	Mudumbi et al. 2014
Water hyacinth (*Eichhornia crassipes* (Mart.) solms)	PFOA	Full	Sediment	–	−0.44	Mudumbi et al. 2014
P. amphibian (*Persicaria amphibia* L)	PFOA	Full	Sediment	–	−0.89	Mudumbi et al. 2014
F. carica (*Ficus carica* L)	PFOA	Full	Sediment	–	−0.92	Mudumbi et al. 2014
A. schmidtiana (*Artemisia schmidtiana* Maxim)	PFOA	Full	Sediment	–	−0.95	Mudumbi et al. 2014
E. horemanii (*Echinodorus horemanii*)	PFOA	Lab	Water	14 d	1.70	Pi et al. 2017
E. horemanii (*Echinodorus horemanii*)	PFOS	Lab	Water	14 d	2.37	Pi et al. 2017
Water hyacinth (*Eichhornia crassipes* (Mart.) solms)	PFOA	Lab	Water	14 d	1.61	Pi et al. 2017
Water hyacinth (*Eichhornia crassipes* (Mart.) solms)	PFOS	Lab	Water	14 d	2.30	Pi et al. 2017
Yam (*Dioscorea* spp.)	PFOA	Full	Soil	–	−0.42	Dalahmeh et al. 2018
Potamogeton (*Potamogeton* sp.)	PFOS	Full	Water	–	3.12	Wilkinson et al. 2018
Potamogeton (*Potamogeton* sp.)	PFOA	Full	Water	–	2.39	Wilkinson et al. 2018
Callitriche (*Callitriche* sp.)	PFOS	Full	Water	–	4.29	Wilkinson et al. 2018
Callitriche (*Callitriche* sp.)	PFOA	Full	Water	–	3.06	Wilkinson et al. 2018
Rush (*Juncus effusus* L)	PFOA	Lab	Water	21 d	0.83	Zhang et al. 2019
Rush (*Juncus effusus* L)	PFOS	Lab	Water	21 d	1.20	Zhang et al. 2019

could be used for PFOA accumulation. In addition, it was observed that the BCF(Log) values of PFOA in *Echinodorus horemanii* were significantly higher than the average, while those of PFOS just reached the average (Fig. 1) (Pi et al. 2017). *Juncus effusus* L was also tested to absorb PFOA and PFOS from aqueous solution in a lab-scale study (Zhang et al. 2019). The results indicated that *Juncus effusus* was more efficient at PFOA than PFOS removal, compared with other species (Zhang et al. 2019). In addition to the above plant species, a list of riparian wetland plants was studied to determine their

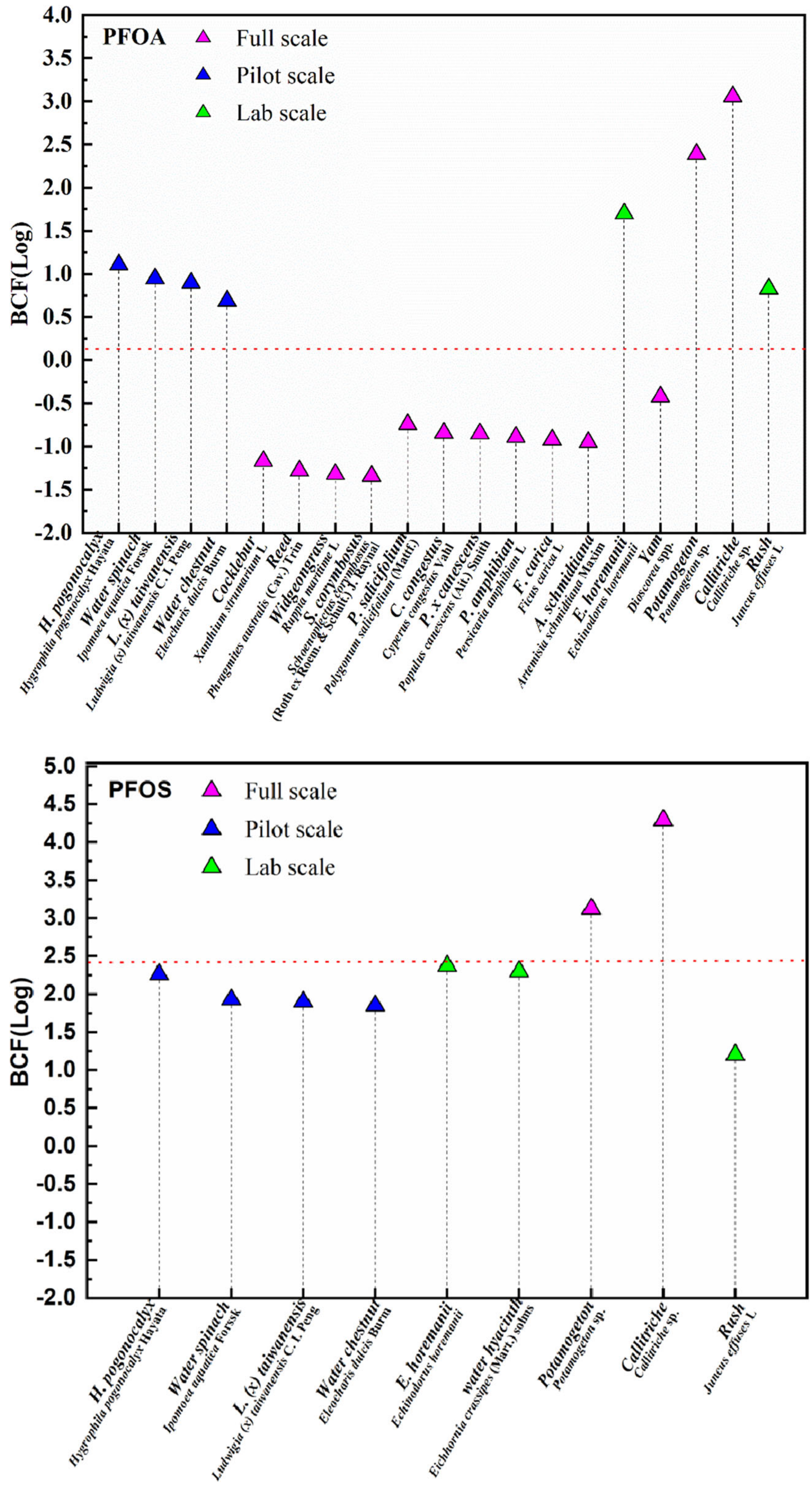

Fig. 1 Comparison of aquatic and wetland plant BCF(Log) values based on a calculated average line (data from Table 1)

susceptibility to PFOA accumulation from PFOA-contaminated riparian sediment (Mudumbi et al. 2014). BCF(Log) indicated that the plants' affinity to PFOA accumulation was *Eichhornia crassipes* (Mart.) solms > *Polygonum salicifolium* (Mattf.) > *Cyperus congestus* Vahl > *Populus canescens* (Ait.) Smith > *Persicaria amphibia* L > *Ficus carica* L > *Artemisia schmidtiana* Maxim > *Xanthium strumarium* L > *Phragmites australis* (Cav.) Trin > *Ruppia maritima* L > *Schoenoplectus corymbosus* (Roth ex Roem. & Schult.) J. Raynal (Mudumbi et al. 2014). Nevertheless, the BCF(Log) values of all of these plants were below the average line as demonstrated in Fig. 1, indicating relative low PFOA uptake efficiency of these plants compared with other plants reported in previous studies. In particular, plants perform differently in various conditions. For example, the BCF(Log) values of *E. crassipes* (*Eichhornia crassipes* (Mart.) solms) were reported to be −0.44 (sediment) in a wetland study (Mudumbi et al. 2014) and 1.61 (water) in a lab-scale study (Pi et al. 2017), respectively.

Terrestrial plants

For PFOA- and PFOS-contaminated soils, there has been a series of studies focusing on PFOA and PFOS uptake using terrestrial plants (Table 2 and Fig. 2). Based on the average BCF(Log) lines in Fig. 2, the relative capacity of each reported plant could be evaluated for potential further application. It is worth mentioning that several plant species (*Tagetes erecta* L and *Bromus diandrus* Roth) were found capable of uptaking both PFOS and PFOA from contaminated soils (García-Valcárcel et al. 2014; Mudumbi et al. 2019). In a lab-scale experiment, approximately 18.1 μg/plant of PFOA and 17.4 μg/plant of PFOS were determined after 20 days, both above the average (Fig. 2) (García-Valcárcel et al. 2014). Similarly, *Tagetes* sp. was applied in accumulated PFOA and PFOS (Mudumbi et al. 2019). High BCF ranges of 1.30 to 2.57 for PFOA and 13.67 to 72.33 for PFOS were obtained from *T. erecta* that suggests a bioaccumulation success (Mudumbi et al. 2019). The above results indicate that the annual grass, *B. diandrus* and *T. erecta*, could act as potential hyperaccumulators for both PFOA and PFOS uptake. Additionally, there were several plant species presenting significant uptake of PFOA or PFOS compared with other species (Gobelius et al. 2017). Norway spruce (*Picea abies* (L.) Karst) that was growing near a fire training facility where soils had been contaminated with PFASs was investigated to evaluate its phytoremediation potential (Gobelius et al. 2017). PFOS uptake measured in Norway spruce was significantly higher than PFOA uptake (Gobelius et al. 2017). Meanwhile, greenhouse and field experiments indicated that *M. truncatula* (*Medicago truncatula* Gaertn) was capable of PFOA uptake in biosolid-amended soils (Lee et al. 2014), while long beechfern (*Phegopteris connectilis* (Michx.) Watt) showed higher PFOS uptake than that of PFOA.

Table 2 The summary of existing PFOS and PFOA uptake in terrestrial plants

Plant	PFASs	Scale	Calculation matrix	Exposure time	BCF(Log)	Ref.
Tall fescue (*Festuca arundinacea* Schreb.)	PFOA	Full	Soil	–	−0.54	Yoo et al. 2011
Bermuda grass (*Cynodon* spp.)	PFOA	Full	Soil	–	−0.89	Yoo et al. 2011
Kentucky bluegrass (*Poa pratensis* Linn.)	PFOA	Full	Soil	–	−0.57	Yoo et al. 2011
Tall fescue (*Festuca arundinacea* Schreb.)	PFOS	Full	Soil	–	−1.12	Yoo et al. 2011
Bermuda grass (*Cynodon* spp.)	PFOS	Full	Soil	–	−1.46	Yoo et al. 2011
Kentucky bluegrass (*Poa pratensis* Linn.)	PFOS	Full	Soil	–	−1.08	Yoo et al. 2011
Brome (*Bromus diandrus* Roth.)	PFOA	Lab	Water	20 d	1.86	García-Valcárcel et al. 2014
Brome (*Bromus diandrus* Roth.)	PFOS	Lab	Water	20 d	1.84	García-Valcárcel et al. 2014
Alfalfa (*Medicago truncatula* Gaertn)	PFOA	Pilot	Soil	165 d	0.16	Lee et al. 2014
Silver birch (*Betula pendula* Roth.)	PFOA	Full	Soil	–	−0.32	Gobelius et al. 2017
Silver birch (*Betula pendula* Roth.)	PFOS	Full	Soil	–	−0.96	Gobelius et al. 2017
Norway spruce (*Picea abies* (L.) H. Karst)	PFOA	Full	Soil	–	1.26	Gobelius et al. 2017
Norway spruce (*Picea abies* (L.) H. Karst)	PFOS	Full	Soil	–	−0.55	Gobelius et al. 2017
Bird cherry (*Prunus padus* L.)	PFOS	Full	Soil	–	−0.96	Gobelius et al. 2017
Ground elder (*Aegopodium podagraria* L.)	PFOS	Full	Soil	–	−0.89	Gobelius et al. 2017
Long beechfern (*Phegopteris connectilis* (Michx.) Watt.)	PFOS	Full	Soil	–	2.69	Gobelius et al. 2017
African marigold (*Tagetes erecta* L)	PFOA	Lab	Soil	–	0.41	Mudumbi et al. 2019
African marigold (*Tagetes erecta* L)	PFOS	Lab	Soil	–	1.86	Mudumbi et al. 2019

The results provide evidence of certain plants selectivity to bioaccumulate chemicals in soils with PFAS contamination. Other plants have been less selective and showed relative low uptake in soils with PFAS contamination (Gobelius et al. 2017; Yoo et al. 2011). The continued screening of plants, in field applications, that act as hyperaccumulators of PFASs is crucial to remediate contaminated sites.

Potential hyperaccumulators

Figures 1 and 2 provide PCF(Log) values for bioaccumulating aquatic and wetland and terrestrial plants at full, pilot, and lab scale with a calculated average line. In sites of wastewater or sediment contamination, *Hygrophila pogonocalyx* Hayata, *Ipomoea aquatica* Forsskal, *Ludwigia* (x) *taiwanensis*,

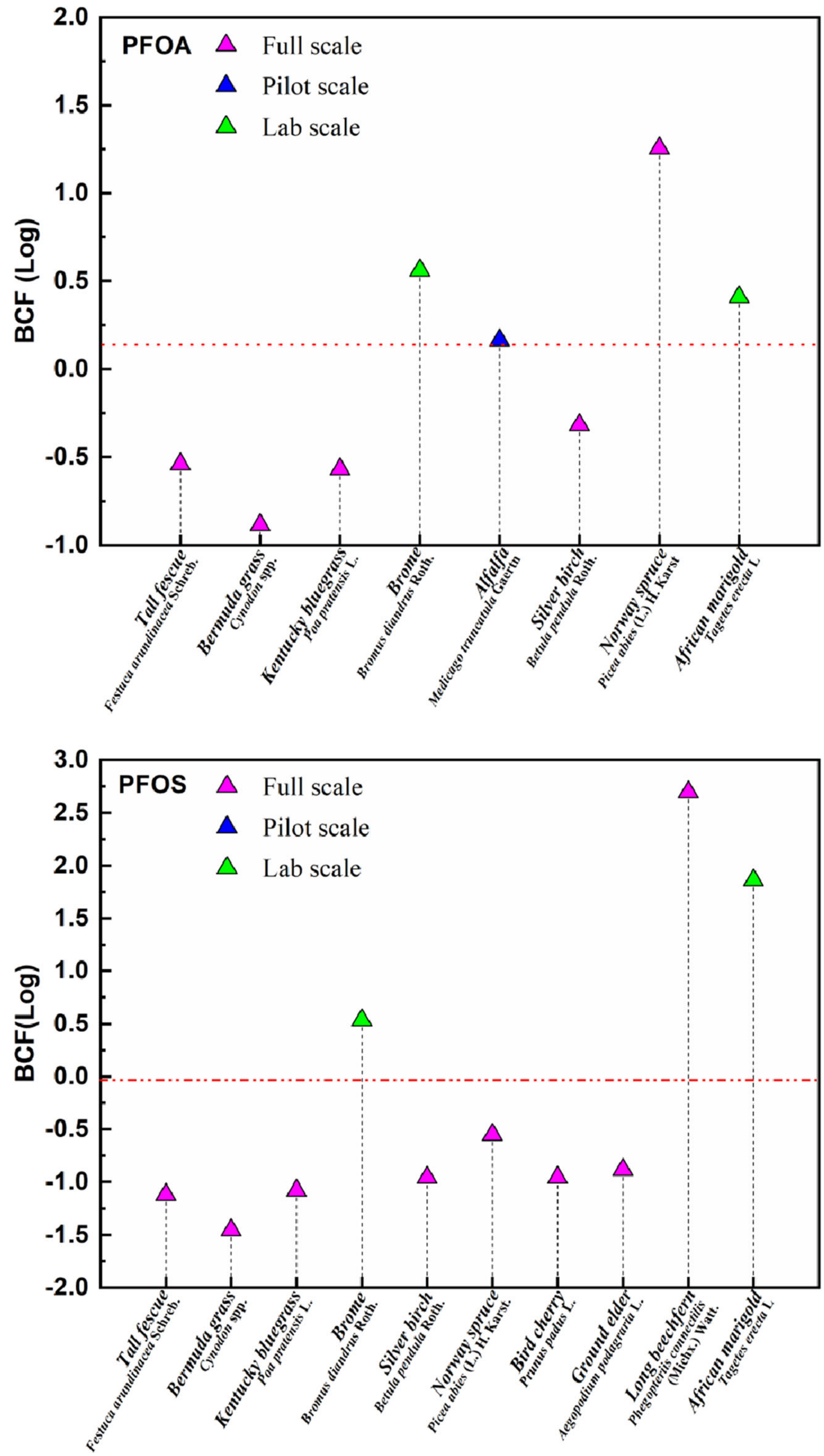

Fig. 2 Comparison of terrestrial plant BCF(Log) values based on a calculated average line (data from Table 2)

E. dulcis, *Callitriche stagnalis* Scop, *Potamogeton* sp., *Echinodorus horemanii*, and *J. effusus* could act as potential hyperaccumulators for PFOA removal. However, the actual performance needs to be confirmed in further field application studies. Among them, *Callitriche* sp. and *Potamogeton* sp. may be capable of PFOS uptake from wastewater or sediment. As for soil remediation, *B. diandrus*, *T. erecta*, Norway spruce, and *Medicago truncatula* could be effective for PFOA uptake from contaminated soils. In addition, *T. erecta* and *F. longipetiolata* performed well for PFOS uptake from soils. *B. diandrus* Roth was observed to be capable of both PFOA and PFOS removal as demonstrated in Fig. 2. These suggestions could provide a reference for future research on PFOS/PFOA phytoremediation.

Particular limitations of the above comparison must be noted as follows. Firstly, the previous studies were conducted in various sites including lab, pilot, and full (field). Uncontrolled external circumstances, such as environmental changes, in pilot and full-scale studies could affect plant uptake performance. Secondly, BCF(Log) is commonly dependent on calculated matrixes. The mass transfer process in lab-scale aqueous solution is undoubtedly higher than that in soils. In this study, soil was chosen as the calculated matrix when both water and soil matrixes existed due to the predominant role of soil adsorption (Chen et al. 2012). Finally, the exposure duration was quite different in various studies, up to 45 days, and BCF(Log) variation may have occurred as time progressed.

Translocation of PFOS and PFOA in plants

Translocation of PFOS and PFOA in reported plants has attracted wide concern due to the substantial connection between phytoremediation potential and pollutant distribution in plant organs. Organic contaminants reach aerial plant organs in two ways: from the air and with the transpiration stream (Huang et al. 2010; Wen et al. 2016). The transpiration stream could be reasonably considered as the crucial mechanism of PFOA/PFOS translocation in plants (Huang et al. 2010, Wen et al. 2016). Plants take up contaminants through roots and transport them to aerial tissues (Madikizela et al. 2018). To assess the translocation potential of PFOA/PFOS in plants, TF (translocation factor) was frequently introduced to quantify the PFOA/PFOS migration (García-Valcárcel et al. 2014; Pi et al. 2017; Wen et al. 2016; Zhang et al. 2019). The plant TFs in previous studies are presented in Table 3. It was obvious that TF was plant species-dependent similar to BCF(Log). For PFOA, TFs of *J. effusus* (Zhang et al. 2019) and *B. diandrus* (García-Valcárcel et al. 2014) were notably higher than others, suggesting higher translocation capacity in these plants. It was worth mentioning that these plants were also superior in PFOA uptake ("Potential hyperaccumulators"). Regarding PFOS, *B. diandrus* presented extremely high TF compared with other species (García-Valcárcel et al. 2014). Meanwhile, *B. diandrus* was concerned due to efficient PFOA uptake. Based on the above results, it could be inferred that high TFs are beneficial for PFOA/PFOS uptake due to the translocation from the root to aerial organs in plants. And then, more PFOA/PFOS uptake would occur in the root with more PFOA/PFOS translocation. More PFOA/PFOS content in the roots and aerial organs means better cleanup from the environmental view. In addition, the protein content of plant tissue was reported to positively correlate with TF of PFOA/PFOS, suggesting TFs correlate positively with shoot to root protein content ratios (Wen et al. 2016). Overall, the TF analysis and comparison could confirm the effectiveness of potential hyperaccumulators for phytoremediation.

Table 3 Transfer factors determined for the different plant applications

Plant	PFASs	Scale	Exposure time	TF	Ref.
Rush (*Juncus effusus* L)	PFOA	Lab	21 d	2.06	Zhang et al. 2019
E. horemanii (*Echinodorus horemanii*)	PFOA	Lab	14 d	0.76	Pi et al. 2017
Water hyacinth (*Eichhornia crassipes* (Mart.) solms)	PFOA	Lab	14 d	0.58	Pi et al. 2017
Brome (*Bromus diandrus* Roth.)	PFOA	Lab	20 d	3.634	García-Valcárcel et al. 2014
Alfalfa (*Medicago truncatula* Gaertn)	PFOA	Lab	45 d	0.304	Wen et al. 2016
Ryegrass (*Lolium multiflorum* Lam.)	PFOA	Lab	45 d	0.563	Wen et al. 2016
Rush (*Juncus effusus* L)	PFOS	Lab	21 d	0.22	Zhang et al. 2019
E. horemanii (*Echinodorus horemanii*)	PFOS	Lab	28 d	0.23	Pi et al. 2017
Water hyacinth (*Eichhornia crassipes* (Mart.) solms)	PFOS	Lab	28 d	0.52	Pi et al. 2017
Brome (*Bromus diandrus* Roth.)	PFOS	Lab	20 d	3.425	García-Valcárcel et al. 2014
Ryegrass (*Lolium multiflorum* Lam.)	PFOS	Lab	45 d	0.131	Wen et al. 2016
Alfalfa (*Medicago truncatula* Gaertn)	PFOS	Lab	45 d	0.131	Wen et al. 2016

Toxic influences of PFOS and PFOA

Biomass

Qu et al. (2010) found that germination of wheat seedlings was stimulated when PFOS concentration in the solution was 0.1–10 mg/L. When PFOS concentration reached 10 mg/L, the biomass of the roots and leaves was significantly inhibited. Compared with the control, the leaf and root length of wheat (*Triticum aestivum* L.) was decreased by 12% and 84.3%, respectively, when PFOS concentration was 200 mg/L, which showed that the root inhibition observed was significantly greater than leaves under the same PFOS concentration (Qu et al. 2010). A similar phenomenon was observed in the soil for *Brassica chinensis* L. root using a standardized root length assay (Zhao et al. 2011). It was found that 50% inhibition (EC_{50}) would be observed when the concentrations of PFOS and PFOA reached 95–4200 mg/kg and 107–246 mg/kg in soil, respectively (Zhao et al. 2011). Another phytotoxicity study showed that PFOA suppressed root and shoot biomass to a much greater extent than sodium fluoride (NaF), and thus, PFOA was much more toxic to *Arabidopsis thaliana* L than inorganic F (Yang et al. 2015). Overall, PFOA and PFOS could inhibit the biomass growth when the concentration reaches a threshold value.

Chlorophyll

Photosynthesis is widely used to characterize a response to various pollutants (Han et al. 2016; Qian et al. 2019; Yang et al. 2017). It was reported that PFOA and PFOS presented negative effects on chlorophyll levels when the concentration reached a threshold value in previous studies (Qian et al. 2019; Qu et al. 2010; Zhao et al. 2017). A previous study showed that the concentration of PFOS (0.1–200 mg/L) was found to decrease the chlorophyll content of wheat; nevertheless, the chlorophyll content was significantly higher than that without PFOS (0 mg/L) after treatment with 0.1–10 mg/L PFOS (Qu et al. 2010). The biosynthesis of chlorophyll (21.92%) in wheat was inhibited after treatment with PFOA (Zhao et al. 2017). Another investigation indicated that the chlorophyll level under the 50 mg/L PFOS treatment decreased by 24.8–38.3%, compared with the control group (Qian et al. 2019). In addition, chlorophyll level did not vary linearly with increasing PFOS concentration (Qian et al. 2019) probably because the chlorophyll variations could be caused by an imbalance between biosynthesis and degradation (Wen et al. 2011).

Soluble protein

Soluble proteins could be employed to reflect plant senescence and photosynthetic intensity (Liao et al. 2000; Majumdar et al. 2014; Qu et al. 2010). The influences of PFOS and PFOA on soluble proteins usually depend on the exposure concentrations (Qian et al. 2019; Qu et al. 2010). It was reported that 0.1–1.0 mg/L PFOS notably accelerated the syntheses of soluble proteins, with a 39.0% increase in under 0.1 mg/L PFOS (Qu et al. 2010). At the 1 mg/L level, the soluble protein content in all samples increased notably in the initial stage probably due to the generation of some stress proteins in plant cells (Qian et al. 2019). However, when PFOS concentration reached to 100–200 mg/L, the soluble protein contents were inhibited significantly (Qu et al. 2010). Similarly, it was observed that PFOS inhibited the foliage in various plants (Qian et al. 2019). Soluble protein content decreased notably compared with the controls when the PFOS concentration increased gradually (Qian et al. 2019).

Enzyme activity

Antioxidant enzymes have crucial roles in plant metabolism, including the responses to external environmental variations. Influences of PFOS or PFOA on antioxidant enzymes were discussed in several previous studies (Qu et al. 2010; Zhang et al. 2019; Zhao et al. 2017). The most frequently reported antioxidant enzymes were superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT). In a *J. effusus* exposure study, the activities of SOD and CAT presented different trends between shoots and roots (Zhang et al. 2019). The activity of SOD in the shoots exposed to perfluorinated substances (including PFOA and PFOS) was significantly higher than that in control shoots on day 21 (Zhang et al. 2019). However, the roots exposed to PFOA and PFOS (10 times dosage) on day 21 had significantly lower SOD activity than the control and the roots (perfluorinated substances at 1 time dosage) (Zhang et al. 2019). As for CAT, a similar phenomenon was observed in the shoots and roots (Zhang et al. 2019). SOD activities in wheat samples were stimulated within the 0.1–10 mg/L PFOS level (Qu et al. 2010). However, when the concentration increased to 200 mg/L, PFOS presented negative influence on the activity of SOD (12.6%) (Qu et al. 2010). Similar trends were observed in POD variations. Positive effects were observed for POD activities in roots with 0.1–10 mg/L PFOS addition (Qu et al. 2010). When the concentration reached 10–200 mg/L, the POD activities were inhibited (Qu et al. 2010). Similarly, the activities of SOD (97.9%) and POD (93.8%) in wheat were inhibited with PFOA addition in a lab-scale study (Zhao et al. 2017). Generally, the inhibition on antioxidant enzymes was more significant in the roots or at high PFOS/PFOA addition.

Oxidative stress

By-products, including reactive oxygen species, are constantly generated during the plant metabolisms (Qian et al. 2019).

A dynamic equilibrium for the content of reactive oxygen species was believed to exist in the complicated system (Majumdar et al. 2014). Reactive oxygen species are usually detrimental to plants when the levels increase to a harmful concentration (50 mg/L) (Qian et al. 2019). Malonaldehyde (MDA) is a by-product of lipid peroxidation and thus could be used for measuring oxidative stress (Qian et al. 2019). It has been confirmed that PFOS and PFOA have a negative effect on plant oxidative stress (Yang et al. 2015). Exposure to 725 μmol/L F (from PFOA) significantly increased shoot MDA concentration by 45% compared with the control in *Arabidopsis thaliana*, whereas no significant effect was observed in the NaF treatment (Qian et al. 2019; Yang et al. 2015; Zhao et al. 2017). The biosynthesis of MDA (60.65%) in rapeseed (*Brassica napus*) was enhanced with mixed PFOA and PFOS addition of 300 ng/g soil (Zhao et al. 2017); however, it was worth mentioning that different plant species had different MDA sensibilities to PFOS and PFOA. It was reported that the biosynthesis of MDA (19.37%) in wheat was inhibited with mixed PFOA and PFOS addition of 300 ng/g soil (Zhao et al. 2017). Nevertheless, most studies still show that PFOA/PFOS aggravates the oxidative stress of plants.

Others

In addition to the above parameters, other variables were used to assess the toxic influences of PFOS and PFOA on plants. The permeability of root cells was investigated under PFOS contamination. The permeability of wheat root cells increased slightly as the PFOS concentration increased from 0.1 to 100 mg/L, whereas the influence increased when the concentration applied was 100–200 mg/L (Qu et al. 2010). Low PFOS concentration could enhance the permeability of wheat root cells slightly, which might be caused by the fact that PFOS was a surfactant which could generally increase the permeability of the plant cell membrane (Qu et al. 2010), and some similar experimental phenomenon had been reported in previous studies (Knoche and Bukovac 2004; Wild and Jones 1992). In addition, integrated biomarker response (IBR) was introduced to evaluate the toxic influences of PFOS/PFOA based on several variables (Qian et al. 2019). The IBR value provides an intuitive evaluation of the organism health (Hou et al. 2016; Qian et al. 2019). Low concentrations of PFOS resulted in greater IBR values than those of the control groups of both species, while inhibition was observed under high concentrations of PFOS (10 mg/L and 50 mg/L) (Qian et al. 2019).

Implications and recommendations for future research

The research on plant uptake of PFOS and PFOA is not extensive, and more detailed studies are necessary for developing efficient phytoremediation technologies. Based on the existing studies, there are several potential research fields.

(1) The disposal to land of biomass wastes containing PFOS and PFOA may become an issue if phytoremediation is practiced as a plant-based solution. A scientific-based cost-effective management solution to reduce any secondary pollution needs to be considered and put in place as a secure technique in the near future.

(2) An understanding of the variability of PFOS and PFOA translocation in plants is urgently needed. Though differences in plant species have been widely investigated and compared, the detailed translocation mechanisms of PFOS and PFOA are still unclear. As the only channel for the migration and uptake of substances in the soil is plant roots, any rhizosphere process affects the availability of PFOA and PFOS directly, changing their stability in the soil, so the effects of rhizosphere microorganisms and root exudates on phytoremediation should be further explored.

(3) The internal metabolic pathways of PFOS and PFOA in plants are not well understood. The mass balance calculation should be designed and carried out to track the movement of the pollutant, either in solution or the soil, and to track the fate and uptake in the functional organs of the receiving plants or environment.

(4) The synergistic treatment of PFOS and PFOA combining phytoremediation and other physical and chemical techniques is promising. Treatment train approaches may prove more successful than single technologies (Kucharzyk et al. 2017).

(5) The connections between soil-porewater-microbe-plants for soil remediation are extremely complicated and elusive. The comprehensive system could be used for explaining the natural processes of PFOS and PFOA.

(6) The evaluating methods normally depend on the uptake variable (BCF) and translocation variable (TF). These variables are built up based on concentration differences rather than total contents. It is undisputed that there are huge differences of biomass among various plants. Therefore, both biomass and concentration should be taken into consideration during the evaluation of phytoremediation efficiencies such as loading that can be used to evaluate the proportion of chemical in various tissues of plant.

$$\text{Loading} = (C_i{*}P_i)/\left(\sum(C_i{*}P_i)\right){*}100\%, \quad (4)$$

where C_i is the chemical concentration, P_i is the percentage of a plant tissue, and i is the corresponding plant tissue.

(7) Economic feasibility should be evaluated before PFOS and PFOA phytoremediation is implemented. Other than physical and chemical techniques, energy and equipment costs are little involved. Thus, the economic cost needs to be rationally assessed with novel methods.

Conclusions

This review summarizes and analyzes the uptake, translocation, distribution, and toxic effects of PFOS and PFOA based on previous studies. It has been demonstrated that *Callitriche* sp. and *Potamogeton* sp. are both capable of PFOS and PFOA removal from wastewater or sediment. As for soil remediation, *T. erecta*, *B. diandrus*, Norway spruce, and *M. truncatula* could be effective for PFOA uptake from contaminated soils. Meanwhile, *T. erecta* and *F. longipetiolata* performed well for PFOS uptake from soils. Translocation analysis indicates that high TFs are beneficial for PFOA/PFOS uptake due to the translocation from the root to aerial organs in plants. In the toxicity investigation, biomass, chlorophyll, soluble protein, enzyme activities, oxidative stress, and other variables are discussed. PFOA and PFOS exerted a negative effect on plant physiology and morphology. Symptoms of PFOA and PFOS include growth inhibition of shoots and roots, decreasing the content of chlorophyll per cell, impairment of photosynthesis, and decreasing soluble protein expression. In addition, the inhibition of PFOA and PFOS on the antioxidant enzymes was more significant in the roots than shoots. It is common that PFOA/PFOS concentrations above the threshold values would cause notable damage to plants. Eventually, implications for future research are provided as a reference for further work. Overall, plant uptake is a promising choice for PFOA/PFOS removal for environmental remediation and cleanup.

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Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

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Conflict of interest The authors declare no competing interests.

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