A REVIEW OF THE OPTIMAL CONDITIONS FOR PHYTOREMEDIATION OF PFAS-CONTAMINATED AGRICULTURAL LANDS

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Abstract

Vegetation that is grown on land contaminated by Per- and polyfluoroalkyl substances (PFAS) will bioaccumulate the contaminant at levels that can cause adverse health effects once consumed by humans. Many groups and government authorities have begun to put restrictions on the application of PFAS, specifically long-chain PFAS (chain length greater than 7 carbons). Phytoremediation is a promising method to absorb PFAS from the soil to be stored in the plant. Soil properties, PFAS chain length, and plant type are all variables that influence the rate of PFAS uptake and storage by plants. Phytoremediation absorbs larger concentrations of short-chain PFAS than long-chain PFAS due to its decreased hydrophobicity and increased mobility. Plants with increased foliage compartments are ideal for this method. Lower organic soil content and increased soil salinity contribute to more uptake. The growing season of plants also contributes to increased uptake. The pH of soil does not have consistent data on whether it increases or decreases PFAS uptake and should be further studied. Plants with larger periods of biomass growth and higher lipid and protein content increase PFAS uptake. Once in the plant most of the PFAS is stored in the vegetative compartments. PFAS absorbed from contaminated land is then stored in these above-ground plant compartments and can be removed from the contaminated site and disposed of.

1. Introduction

PFAS are a group of manmade chemicals that have been in use since the mid-1900s (Buck et al., 2011; Blake et. al, 2020). One concern with PFAS are its negative impacts on human health (Blake et al., 2020). They are known to cause health concerns including adverse pregnancy outcomes and thyroid, kidney, and liver issues (Blake et al., 2020). A major pathway for PFAS to enter the human body is through the consumption of water or food from contaminated environmental sites (Kavusi et al.., 2023). Bioaccumulation of PFAS within the body is a great concern for long-term adverse health effects.

With this threat of PFAS, it is important to find viable methods to remove PFAS from the environment to ensure the consumption of healthy non-contaminated vegetation. Bioaccumulation is the build-up of substances within plants or humans over time. PFAS bioaccumulates in humans and plants during periods of increased exposure. This concept of bioaccumulation makes phytoremediation, the removal of a contaminant using plants, a promising method for PFAS removal from the soil matrix (Kavusi et al., 2023; Mayakudawage et al., 2022). This process involves the uptake of a contaminant from the soil pores. The goal of this uptake is the translocation and thus bioaccumulation of the targeted contaminant (PFAS) within the above soil compartments of vegetation. Translocation of PFAS is the movement of PFAS from the pore water, through the roots to then be stored within other compartments of the plant. Once phytoremediation occurs the plants will need to be removed so that the PFAS does not reabsorb into the field it was removed from.

1.1 Background Information on PFAS

PFAS have vast application potential to increase stability in everyday products and in the creation of oil, water, and fire-retardant products, which has made them ubiquitous in consumer products today. PFAS are found in specific products such as Gore-Tex, Teflon and more generally they are found in food packaging. A recent study found a major global source of PFAS in wastewater treatment systems to be PFAS in toilet paper (Thompson Et al., 2023). Wastewater treatment plants have been shown to significantly contribute to the proportion of PFAS in the environment (Zhou et al., 2017). Other than these treatment plants, there are multiple pathways by which PFAS enters the environment, such as industrial site disposal and via the use of aqueous fire-fighting foams (AFFFs) (Gobelius et al., 2017). AFFFs can extinguish fires caused by flammable liquids and are commonly used at airfields, military bases, and other firefighting training facilities. It should be noted that very small amounts of PFAS, on the part per billion scale, cause many problems.

PFAS has recently had a great surge in interest in the scientific community, and because of this the terminology and knowledge of PFAS have changed in recent years. Due to its prevalence and adverse impacts, many different constituencies are now interested in PFAS: scientists, water managers, regulators and enforcement, policymakers, manufacturers, environmentalists, community groups, and public health advocates. Many of the papers used in this review refer to PFAS and its different compounds by various names. In this review, the greater overall substance will consistently be referred to as PFAS, the most modern and encompassing name for the substances (Buck et al., 2011). Any other titles used, such as PFAS and PFOA, are specific PFAS.

PFOA and PFOS are just two of more than 4,700 distinct PFAS compounds that have been used commonly since the early 1980s (oecd.org, 2021). A major challenge with understanding PFAS is that there are so many different types of PFAS, and each may present different characteristics and act differently. Notably, chain length has been one variable that can be used to find commonalities to classify the over 4,700 PFAS. The Organization for Economic Co-operation and Development (OECD) defines long-chain PFAS as compounds with seven or more carbon atoms in the chain. Some common long-chain PFAS are PFOS and PFOA, while short-chain PFAS include perflourobutanoic acid (PFBA) and perfluorobutane sulfonate (PFBS) (oecd.org, 2021).

1.2 Governmental Restrictions

With the escalation of research and understanding of the negative impacts of PFAS, many governments and groups have begun to place restrictions on the contaminant. In 2012, the EPA announced drinking water health advisories and levels of concern for two types of PFAS: PFOA and PFOS. More recently, on August 26, 2022, they designated those same two types as CERCLA Hazardous substances. Since the initial advisories of PFOA and PFOS, four other types of PFAS have also been given health advisory limits (EPA.gov, 2023).

The Stockholm Convention lists PFOS as a restricted Persistent Organic Pollutant (chm.pops.int). In January of 2023, five European nations submitted a proposal to ban the use of PFAS throughout Europe (rivm.nl). In the USA, the EPA has restrictions on the import and use of long-chain PFAS (epa.gov, 2023). Other nations such as Canada and China have also placed individual regulations of long-chain PFAS. These regulations have led to a shift from the originally prevalent long-chain PFAS to a new urgency of short-chain PFAS. Most of the original PFAS used in large quantities were considered long-chain. Once they were found to have high bioaccumulation potentials, persistency, and toxicity, short-chain PFAS began to be used more in production. These shorter-chain PFAS can often be used for the same products as long-chain PFAS and are less regulated and harder to research due to their high mobility. The short-chain PFAS have a much shorter half-life meaning they remain in the body for a shorter amount of time, but they still accumulate at toxic levels and should be considered a substance of concern (Brendel et al., 2018).

1.3 Phytoremediation

Despite widespread concern over PFAS, they persist in ecosystems, and humans are still exposed to the contaminant at higher than recommended rates. PFAS can be removed or “filtered” from different environmental media using specific methods. A practical filtration system for PFAS-contaminated land mass is not yet established, this review will analyze phytoremediation as a viable method.

Much of the research on the phytoremediation of PFAS has been done with wetland species rather than terrestrial vegetation (Huff et al.). PFAS remediation techniques that have been completed on hydroponically or wetland-grown plants have not been compared to differences in terrestrial (soil-based) plants (Mayakaduwage et al., 2022). In aquatically grown environments phytofiltration occurs as opposed to the phytoextraction that is in terrestrial plants, this could cause differences in how PFAS bioaccumulates (Kavusi et al., 2023).

For some contaminants, phytoremediation can involve the degradation of the substance, but current research has not shown PFAS to readily degrade once absorbed in plants. This phytoremediation would not provide actual degradation of PFAS but rather a pathway to remove PFAS from a targeted area (Shahsavari et al., 2021). After it is absorbed into the vegetation, the plants must be removed from the land so that the contaminant is not reabsorbed into the environment when the plants die.

This removal process generally involves the complete removal of the top layer of land to remove all the collected PFAS. With the goal of this review being to revive soils for agricultural methods, the entire removal of the top layer of soil is not ideal for overall soil health and regeneration as that would remove many vital nutrients and minerals from the soil. If the top layer of soil were removed the soil would then have to go through a regeneration and fixation process after the PFAS removal, adding years to the remediation process. Thus, the removal of vegetation only the above soil layer (plant shoots) would allow for ample plant growth and removal.

1.4 Introductory Findings

A main aim of this review is to analyze the conditions for which PFAS is known to absorb at the highest concentrations in plants. The rate of uptake will be dependent on both the makeup of the soil matrix and the plant. Different parts of a plant are found to store PFAS at increased levels once absorbed and translocated from its root system (Xu et al, 2022; Liu et al., 2019; Gobelius et al., 2017). The makeup of a plant, such as its lipid and protein content will also impact absorption (Wen et al., 2016). The relationship between PFAS bioavailability for plant uptake is highly dependent on the conditions of the soil matrix, such as pH, organic matter content, and salinity. These absorption factors were analyzed, and a conclusion was made on optimal methods for PFAS removal from soil. Evidence is often conflicting due to the variability in the types of PFAS and how the different structures may be absorbed into soil pores and thus by the plant at different rates. In the end, this understanding of optimized bioaccumulation of PFAS will present conditions that could best be used to remediate contaminated agricultural lands so that this land can be used for agriculture again.

2. Methods

The methodology used to complete this review was a systematic evaluation of primary scientific literature via online article databases and repositories. These articles discuss the accumulation of PFAS in plants and specifically what conditions led to the greatest concentrations of accumulation. Some of the papers put forth unique research and others were literature reviews encompassing new findings. Science Direct and the American Chemistry Society Publications were used to locate and access many of the papers.

One commonality noticed in collecting data for this review is that much of the research on this topic has occurred in East Asia. This could be due to a shift from the production of PFAS in the United States and European Nations after the introduction of restrictive agreements that did not occur in East Asia.

3. How do plants absorb PFAS:

PFAS enters a plant's ecosystem generally in liquid forms and is absorbed into soil and pore water following concentration gradients. PFAS is mostly bioavailable to the plant roots in the pore water (Brusseau et al., 2022). The roots will uptake the PFAS due to the gradient between their roots and the pore water. Concentration gradients consistently drive the uptake of water and other substances from soil to plants. Lesmeister et al., considered it an important factor to note if the bioaccumulation factors (BAFs) of plants were based on PFAS levels in the soil or from the pore water (2021). A vital understanding is that PFAS must first dissolve in pore water to be readily available for plant uptake.

Research often ignores that water and soil are interrelated, stating that plant exposure to PFAS is either from water or soil. The process of PFAS being absorbed from the environment into plants is very interrelated between water and soil. Due to concentration gradients, the reaction between soil, water, and the plant cannot be decoupled and it is thus important to specify the correlation between water and soil contamination to understand the uptake of PFAS in plants.

One clarification that can be used moving forward is specifying BAFs as water-plant BAF or soil-plant BAF. This should be heavily distinguished in future papers as BAF is calculated using:

$$BAF = \frac{PFAS\ concentration\ in\ plant}{PFAS\ concentration\ in\ specific\ media} \qquad \textit{Equation 1. Modified from Xu et al.}$$

The water-plant BAF in this situation would account for PFAS concentrations in aqueous media either in wetlands, pore water, or the hydroponics system the plant is growing in. The soil accounts for PFAS concentrations in the sediment/soil in the area the plant is growing in.

PFAS are known to consistently be present in higher levels in plants when there are higher levels in the plant's environment (Brusseau et al., 2022). Figure 1 depicts how plants' roots absorb pore water (and thus PFAS) and then spread it to the other parts of the plant in the process known as translocation. By focusing on translocation and bioaccumulation, this paper will investigate how different soil characteristics can affect the equilibria and therefore the amount of PFAS present and readily available.

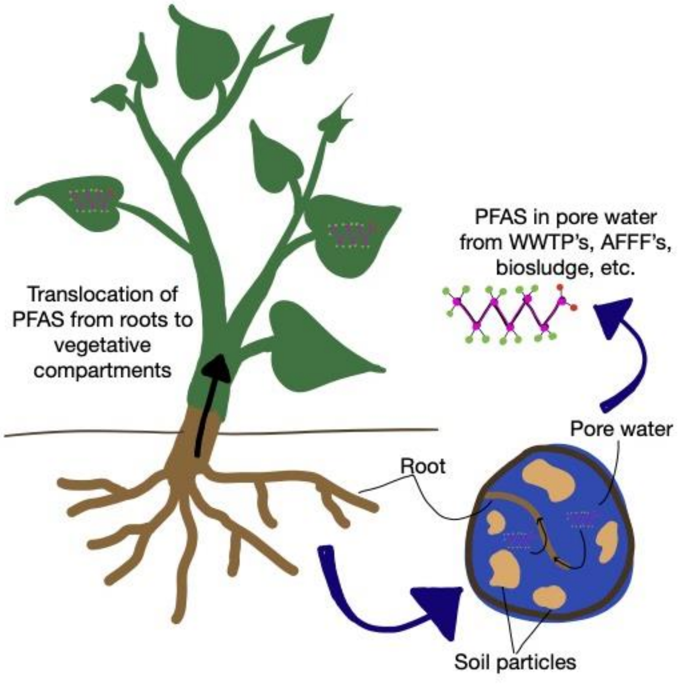

Figure 1 Translocation of PFAS from soil pore water to plant compartments

4. How PFAS get into agricultural lands and humans

Studies on the bioaccumulation of PFAS have concluded that the consumption of vegetables and other produce grown in PFAS-contaminated water and soils are an exposure pathway of PFAS in humans (Shan et al., 2016; Lesmeister et al., 2021; Liu et al., 2019). This is detrimental for farms and other agricultural lands near PFAS expulsion sites, military bases, and firefighting training areas. The water that becomes contaminated with PFAS in the areas surrounding these sites then is then used to irrigate agricultural land. This provides a pathway to harm humans through drinking and eating food grown with soil contaminated by this PFAS-contaminated water (Kavusi et al., 2023).

Brusseau et all. stated that soil is considered a significant reservoir for PFAS, finding that in contaminated areas PFAS levels appear magnitudes higher in soils than in groundwater (2022). This high amount of PFAS in groundwater has been a main contributor to PFAS in plants. Absorption from the pore water in PFAS-contaminated soils is the predominant reason PFAS are found in plants (Xu et al., 2016, Figure 1). Zhou et al. stated that the main cause of PFAS in vegetables is from surface and ground waters (2021). As noted in section 3, literature often switches between either water or soil as pathways for PFAS. Based on this discrepancy, it remains important to note the interrelatedness of the PFAS in soil and water. One example of this interconnectedness is how irrigation from polluted water sources and aquifers is a direct way that PFAS can enter the soil and bioaccumulate in plants.

Studies have shown, whether focusing on water or soil, that PFAS is also available to be absorbed by vegetation due to its presence in pesticides, biosolids, and sludge (Blaine et al, 2014), and wastewater irrigation (Shan et al., 2016; Zhou et al., 2017). Bio sludge and recycled water are all commonly used in agricultural practices (Blaine et al. 2014 and Wu et al.). Bio sludge allows for ideal nutrients to be added into the soil so that plants can have more growth. These all provide a pathway for PFAS to enter agricultural lands and thus enter people’s bodies through produce grown on such lands (Shahsavari et al., 2021).

In addition, some studies have suggested that PFAS contamination can also occur through aerial PFAS deposition (Liu et al., 2019), but in this paper that is not considered a major pathway as it has been found to have negligible impacts (Wen et al., 2016; Zhao et al., 2014). Aerial PFAS is the occurrence of concentrations of PFAS found in the air or atmosphere. This can occur through the direct application of PFAS in aerosol form and as a byproduct of sea spray (Faust, 2023). Another pathway of PFAS from contaminated fields to humans is from the consumption of meat products that come from animals fed contaminated feed. Lesmeister et al. expressed that while the PFAS-contaminated soils contribute to human exposure to PFAS through agriculture, many factors influencing that pathway are not fully understood (2021).

5. PFAS variables causing differences in uptake

The many different types of PFAS are often found to act similarly based on chain length. Shorter chain PFAS are more soluble and less hydrophilic and thus have greater mobility and higher uptake levels (Gobelius et al., 2017; Liu et al., 2019). Although hydrophilicity plays a large role in PFAS bioavailability, research is inconsistent on whether longer-chain PFAS increases (Zhou et al, 2021; Shahsavari et al., 2021) or decreases (Buck et al, 2011, Lesmeister et al., 2021, Liu et al., 2019) bioaccumulation potential.

Liu et al. suggested that shorter-chain PFAS were less predominant (PFOA in this review) in the reference areas and yet were the major contaminants in some crops due to bioaccumulation preferences (2019). Later, they specified that this could be a result of the limited use of long-chain PFAS in this area. This presents a question of whether the longer-chain PFAS were missing because of bioaccumulation preferences or absent from the plant’s environment in the first place. This lack of long-chain PFAS in environments could be a response to the placement of stricter restrictions on PFAS from governments and agencies.

Lesmeister et al. and Park et al. both studied chain length and hydrophobicity as absorptive factors. By nature, PFAS have a hydrophobic chain and a hydrophilic head. Chain length is relative to the hydrophobicity of a molecule and as the chain length increases the hydrophobicity of the compound increases (Lesmeister et al., 2021; Park et al., 2020). These longer more hydrophobic PFAS bioaccumulate in plants at lower rates than shorter and thus less hydrophobic PFAS. Due to the effects of hydrophobicity, BAF decreases with increasing chain length (Lesmeister et al., 2021).

When looking specifically at the pore-water-to-plant BAF relationship, longer-chain PFAS are more hydrophobic and will thus absorb more in soil and have less mobility. Due to hydrophobic tendencies longer chain PFAS are more concentrated in the soil while the shorter chain is in the pore water. The position of longer chains will lead to a lower uptake as they are not as present in the pore water as the more mobile short-chain PFAS.

Results have varied slightly in each study on whether longer or shorter-chain PFAS will be observed in higher concentrations in plants. In this paper, it will be considered resolved that for plants grown in soil, BAFs are higher for shorter-chain PFAS (Lesmeister Et al., 2021; Park et al., 2020; Eun et al., 2020). It should be noted that the effects of branching or linear chain length on absorption factors have not been evaluated in this review, as data on these effects are limited in the literature. Branching originally occurred as a byproduct of intended linear chain PFAS and should be studied further to identify differing behaviors from linear PFAS (Schulz et al, 2020).

6. Plant compartments containing the highest concentrations of PFAS

Due to how different PFAS interact with soil and plants there is conflicting data published on which parts of a plant accumulate the highest concentrations of PFAS. Leaf vegetables show higher PFAS accumulation levels than root vegetables, which in turn were, higher than flower vegetables, and the lowest concentrations were recorded in shoot vegetables (Xu et al., 2016). This opposed the results from Liu et al. with PFAS concentrations being the highest in shoot vegetables, then fruit vegetables, flower vegetables, root vegetables, and lowest in grain crops (2019). Thus, there is conflicting data on which types of plants are seen to contain the highest concentrations of PFAS. More research could be done on this because of the conflicting data.

One way that plant absorption is studied is by breaking plants down into compartments. Starting with roots (parts of the plant growing below ground) and shoots (parts of the plant growing above ground). Within the shoots, there are different compartments, some of which are the stem, buds, and leaves. Different plants will have larger leaves or more woody features and these differences can change the way that PFAS is stored. Foliage (also referred to as leaves and vegetative compartments) was reported most consistently to have accumulated the highest concentrations of PFAS (Liu et al., 2019; Gobelius et al. 2017). A tendency of higher concentrations in the foliage in birch and elm trees was found as opposed to the twigs, stems, and roots (Gobelius et al., 2017). Huff et al. studied the concentrations of PFAS in eight herbaceous and seven woody plants. They found that the concentrations in wood were much lower than in foliage, often with negligible concentrations. Thus, there is compelling evidence that the vegetative compartments of plants have the highest BAFs (Lesmesiter et al., 2021) in comparison to the BAFs found in storage and/or reproductive organs. This is supported by the logic that leaves store the most water in plants. For optimal phytoremediation and PFAS removal, plants with a large percentage of foliage should be used. Future studies should research which types of leafy plants are better able to absorb PFAS to identify the type of plant species that should be used in this method.

7. Chain length and plant compartments

PFAS have been seen to accumulate in plants at different concentrations based on chain length. Short-chain PFAS accumulate in both the leafy and fruit compartments of plants with higher concentrations than recorded in the leaves. Long-chain PFAS did not have as high translocation rates as short-chain PFAS in these plants. About 15% of a short-chain PFAS concentration in the test solution was translocated into the stem of the plants (Felizeter et al., 2014)

In some studies, on plant roots, it was found that root compartments contain the highest concentrations of PFAS (Zhou et al., 2017; Wu et al.), specifically long-chain PFAS (Xu et al. 2022, Felizeter et al., 2014, Zhang et al.). This review is focusing on the above-ground plant compartments. Roots will not be fully removed from the environment for soil nutrient retention purposes in this remediation portion method. The final goal of this review is to present optimal conditions to extract the

PFAS to later use the land for agricultural purposes, thus it is best to focus on plant components above ground that collects high levels of PFAS and are the easiest to remove from ecosystems.

It is important to consider the retention of absorbed PFAS in roots and the effect that chain length has on the translocation of PFAS in plants. The short-chain PFAS are more mobile in the pore water and translocate to foliage at higher rates than long-chain PFAS, thus short-chain PFAS are often found at higher concentrations farther up the plant (Gobelius et al., 2017).

8. Current remediation methods

Due to this review's focus on above-ground removal, methods that are found to encourage the translocation of longer-chain PFAS from root to shoot were important to consider. Xu et al. conducted a study on how the addition of copper oxide nanoparticles (nCuO) could enhance the bioaccumulation of PFOA in radish (2022). It was found that the composition of PFOA in the shoots of the radish was about two times higher than that in the roots, meaning that the PFAS was no longer under the soil layer but in aboveground plant compartments. This was promising to show how bioaccumulation in vegetables can be used as a potential phytoremediation strategy (Yu et al., 2018). The addition of nCuO more than doubled the transport of PFOA from the roots to the shoots. This is important to consider as nCuO could be used to enhance the phytoremediation of PFOA and other long-chain PFAS. Yu et al. found that one way to continue farming on PFAS-contaminated agricultural lands would be to plant low-pollutant cultivars that could then have uptake concentrations that are low enough for consumption (2018). These are two examples in which remediation through plant uptake of PFAS that have been noted as successful. Specifically with the application of nCuO enhancing bioaccumulation, methods like this can be used to improve phytoremediation techniques.

9. Plant variables causing differences in uptake

9.1 Plants with Larger Periods of Biomass Growth

A period of greater biomass growth is noted as superior to periods of less growth for PFAS absorption (Huff et al., 2020). This presents the idea that trees and other longer, larger, growing species could be adequate for phytoremediation of PFAS but more research is needed to quantify how much more effective removal of PFAS with trees could be. PFAS has also been shown to continuously accumulate in plants without a concentration maximum (Huff et al., 2020). Without a maximum, there is great potential for PFAS to accumulate in plants and at larger rates in plants with increased biomass growth.

9.2 Plant Lipid and Protein Content

Protein and lipid levels are seen to affect both the uptake of PFAS into a plant and the ability of PFAS to be translocated throughout the plant. PFAS are amphiphilic, which results in ready accumulation within lipids and proteins (Shahsavari et al., 2021). Due to the hydrophobic character of PFAS, they are more likely to bind to high lipid-containing plants (Zhou et al., 2021; Lui et al.). Thus, lower protein content has been found to result in lower levels of PFAS accumulation in plants (Yu et al., 2018).

Wen et al. found a correlation between plant shoot concentration factors and shoot protein content. From an analysis of findings, the PFOS concentrations found in the roots of plants increased with increased protein and this correlated to the amount that was then translocated to the stems or shoots (2016). The lipid and protein content of the shoots then allowed for higher concentrations of PFAS in the shoots of plants. Thus, plants with high lipids and protein throughout their compartments will increase the translocation of PFAS from soil to root to shoot. This movement to above-ground compartments is important in this review as the optimal treatment of the now PFAS-contaminated plants will only remove the compartments above the soil level.

10. What soil properties make PFAS accumulate more

Different qualities in the soil can have an impact on the concentrations of PFAS that can be absorbed from the soil by plants. Factors such as seasonality, pH, salinity, and soil organic content have been studied to conclude if they would contribute to higher or lower levels of absorption.

10.1 Seasonality

It has been suggested that seasonality contributes to a variance in plant uptake of PFAS compounds (Gobelius et al., 2017; Zhou et al., 2017). Zhou et al. studied wetland species PFAS absorption and found that seasonal trends affect the mean concentrations of PFAS in the environment with it highest in summer, next in spring, then much lower in the fall, and the least in winter (2017). However, for each different PFAS compound, there were unique seasons in which they would appear in the highest concentrations with short-chain PFAS dominating seasons of high river flux and longer-chain PFAS dominating in fall and winter. It should also be considered that this may be dependent on production changes and release at the nearby factories instead of natural environmental seasonal impacts.

10.2 Salinity

The effect of salinity was seen to increase the absorption of most types of PFAS. One study observed that the increase was often without statistical significance (Huff et al., 2020). In hydroponically grown species of wheat, it was found that higher levels of salinity led to greater concentrations of PFAS found in the plant organisms. In another study the greatest increase in concentration was found in the roots as opposed to the shoots of the plant for PFAS but PFBA (Zhao et al. 2016). This is important to note due to its significance in PFAS entering the plants' system, but not vital to the focus on shoot plant removal in this review. When observing the shoots, there was an increase in shoot concentrations of PFAS with increased salinity, but these values were barely significant in comparison to the increases in root concentrations.

10.3 Soil Organic Matter

Soil organic matter was found to have an inverse relationship with the uptake of PFAS in plants (Xu et al., 2022); When the amount of soil organic matter increases, that leads to a decrease in PFAS uptake. This is because an increase in soil carbon causes more particles to bind with the soil reducing the amount of PFAS in water pores and therefore readily available to be taken up by the plant. In industrial agricultural lands, much of the soil has been depleted of much of its organic content. With this in mind, lower soil organic matter is beneficial to the removal of PFAS through phytoremediation because more PFAS is available in the pore water that is readily available for absorption by the plants. This was found to be consistent with other studies and should be considered a resolute finding in this review (Shahsavari et al., 2021).

10.4 pH

The data on whether higher or lower pH will lead to greater absorption of PFAS in plants vary greatly in current literature. Soil consisting of lower ionic exchange and less organic matter presented PFAS in conditions more readily available for plant uptake (Huff et al., 2020). A study of PFAS root uptake in maize at pH of 5, 6, and 7, found only that perflourodecanoic acid (PFDA) had a decrease in uptake with increased pH. This suggested that low pH values can increase the protonation of some PFAS, but this trend was not followed for the other PFAS tested. This suggests additional factors may be more influential and consistent in the uptake of PFAS by plants (Krippner et al., 2014).

In addition, the type of PFAS such as anionic, ionic, and zwitterion PFAS, can cause differing interactions with soil pH (Nguyen et al., 2020). Nguyen et al. found that it is also possible that chain length will be a corresponding factor between PFAS type groupings for its relationship with pH, such that shorter chain PFAS are less pH sensitive (2020). Some PFAS are negatively charged acids, thus meaning that lower soil pH could present these acidic PFAS as readily bioavailable to plants. For these anionic PFAS, it was found that the soil sorption coefficient decreased as pH increased (Nguyen et al., 2020). PFAS would be retained more in low pH soil similar to the relationship with soil organic carbon, making it less available for absorption into vegetation. The understanding of the impacts that soil pH has on PFAS uptake in plants is quite contradictory and needs further review before it can be considered concrete.

11. Analysis

Many of the above sections are heavily correlated and dependent on one another. Together they can put forth an optimal method for phytoremediation as a promising way to remove PFAS from contaminated agricultural lands. Ideally, these soil conditions will be able to successfully remediate contaminated areas to the point that they can be used as agricultural land in the future.

The relationship between PFAS and plants that increase absorption should be taken into consideration. This means it is ideal to have a soil area with low soil organic carbon and higher salinity. It would also be most optimal to have plants with large amounts of vegetative surface areas and with high protein and lipid makeup. This would be best for extracting all types of PFAS but must be noted that shorter-chain PFAS will be translocated to the above-ground components of plants at significantly higher levels than long-chain PFAS. This is not substantial for areas with high PFOS and PFOA contamination, but the addition of nCuO could provide higher uptake percentages of those PFAS from the soil.

In commercialized agriculture production, much of the land has been deprived of soil organic matter. This is not an ideal practice for nutrient-rich produce but is helpful in the removal of PFAS. These areas are well suited for the removal of PFAS as mentioned previously and vegetation will be able to readily absorb more PFAS. In areas like this, nitrogen-fixing plants can be added to the seed mixture to begin to create a healthy soil mixture for when the PFAS has been successfully removed and the land is ready for agriculture. More research should be done in which specific plants and conditions are tested on a contaminated plot. Most studies have focused on the absorption of PFAS in specific crop or agricultural plant species (Blaine et al. 2014; Mayakaduwage et al., 2022), but for the best phytoremediation potential, it would be beneficial to complete studies that broaden the species under study to other categories of vegetation such as weeds and native species.

After the contaminant has been absorbed, it should not just decompose back into that environment. Unless it is removed it will reenter its environment as it is not readily degraded by the plants. This means that the vegetation must be removed and disposed of elsewhere, generally through incineration. Future studies should be done on the amount of degradation that occurs in plants or if certain plants would contribute to higher levels of PFAS degradation. This would show that if the plants were to decompose, PFAS concentrations would be lower than previous levels or remain the same.

11.1 Removal Process

To complete the removal process in the best way plants that retain PFAS in above-ground compartments (not in the roots) were optimized in this proposal. This could be done using routine mowing and then collection and transportation of the plants rather than a full disruption of the soil matrix. In the yearly schedule, it would be recommended to harvest the growing plants as a normal crop that would be harvested throughout the year, leaving the soil intact with nutrients, vegetation, and roots. Various plant species, specifically species with a higher ability to translocate PFAS from their roots to other plant components, can be used throughout the different seasons so that the remediation period can progress in the quickest but most productive timeline possible.

Ways to dispose of the PFAS-contaminated vegetation without putting communities and environments at risk include removal of the roots containing PFAS and transport to a dumping/contamination collection site for incineration. One of the challenges with this removal method is keeping communities safe when the waste produced must go somewhere. It is vital to keep communities already disproportionally at risk from environmental issues from further harm when developing waste management for PFAS-contaminated plants.

This review does not acknowledge the effect that microorganisms in the contaminated environment could have on phytoremediation and that should be studied more concerning the removal of PFAS (Thijs et al., 2016). Further studies are necessary to understand the best process to deal with PFAS-contaminated vegetation after removal. The suggested method here is incineration as atmospheric deposition does not appear to be a high contributor to PFAS contamination. The degradation of PFAS through incineration must be studied more as the literature currently does not provide concise data.

12. Conclusion

PFAS exposure causes adverse health conditions, which is why it is a contaminant of concern. Humans are exposed to PFAS through the consumption of contaminated food and water. PFAS enters the environment from wastewater treatment sites, AFFFs, and industrial disposal. These PFAS expulsion methods contaminate waterways which are then used to irrigate agricultural lands. PFAS is then translocated from pore water into plant roots and then bioaccumulated in shoots. This pathway by which humans are exposed to PFAS can be altered as a method to remove PFAS from contaminated lands through phytoremediation.

These plants can be optimized to uptake as much PFAS as possible with the goal of reducing PFAS levels in the soil to a point in which it can be healthy for food production once more. Rather than consuming the now-contaminated plants, they can be removed and disposed of. The optimal conditions for this removal of PFAS through phytoremediation vary depending on the qualities of the soil, PFAS type, and plant type. Soil with lower organic content, seasons of increased growth, and increased salinity all increase the bioaccumulation factors of PFAS within plants. The effects of soil pH do not have a consistent understanding in literature and should be further researched. The chain length of PFAS has an inverse relationship with uptake, meaning short-chain PFAS are more likely to be absorbed due to their lower hydrophobicity and increased mobility. This method of phytoremediation works for both short-chain and long-chain PFAS but has higher rates of success for short-chain PFAS.

Plants with higher lipid content, protein content, more vegetative compartments, and larger periods of biomass growth are seen to increase uptake. With the ideal removal occurring above the soil level, the knowledge that the foliage of plants will store high concentrations of PFAS supports using phytoremediation. The rate of PFAS uptake in plants with a high percentage of vegetative compartments should be observed and compared in future studies to find specific vegetation that can be used in an optimized PFAS phytoremediation experiment. These conditions such as soil organic matter, salinity, PFAS chain length, seasonality, and ideal plant compartments can contribute to an optimized environment for the removal of PFAS through phytoremediation.

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