**NEW YORK STATE WATER RESOURCES INSTITUTE**

Department of Biological & Environmental Engineering

B60 Riley-Robb Hall, Cornell University

Ithaca, NY 14853-5701

t 607.254.7163 | f 607.255.4449 | nyswri@cornell.edu

**Literature Review**

Student(s): Tomás Schmieder & Adrián Cardona Young

Mentor(s): Dr’s Natalie L. Cápiro, Pengfei Yan, & Sheng Dong

Project Title: Assessment of Environmental Factors Impacting the Biotransformation of Per- and Polyfluoroalkyl Substances in Recycled Biosolids

**Introduction:**

This deliverable is a literature review on the current state of understanding PFAS in biosolids. Information includes background on PFAS, biosolids use in New York State, the issues of PFAS in biosolids, factors that influence the movement of PFAS in biosolids, experiments that studied the interaction between PFAS in biosolids, and potential remedies for removing PFAS from biosolids.

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**Acronyms:**

AFFF: Aqueous Fire-Fighting Foam

DEC: Department of Environmental Conservation

diPAPs: Polyfluoroalkyl phosphate diesters

EPA: Environmental Protection Agency

FDA: Food and Drug Administration

FTSA: Fluorotelomer sulfonic acids

NYS: New York State

PFAAs: Perfluoroalkyl acids

PFAS: Per- and poly-fluoroalkyl substances

PFBA: Perfluorobutanoic acid

PFBS: Perfluorobutanesulfonic acid

PFHxA: Perfluorohexanoic acid

PFOA: Perfluorooctanoic acid  
 PFOS: Perfluorooctane sulfonate

PFPeA:Perfluoropentanoic acid

SUNY ESF: State University of New York Environmental Science and Forestry

WWTPs: Waste Water Treatment Plants

**PFAS Background**

PFAS are a group of tens of thousands of synthetic compounds used in consumer products and industrial production since the mid-1900s. They have become an essential ingredient in numerous products that are used in our everyday lives. These compounds have been used for their properties to resist heat, grease, oil, and water. They are made up of carbon-fluorine chains, and the bond between C-F is the strongest in organic chemistry, making these chemicals incredibly difficult to degrade, thus causing them to accumulate in their environment. Certain PFAS compounds have been phased out and halted production due to their health concerns, for example, in February 2024, the US FDA announced that grease-proofing materials, PFAS, are no longer being sold for use in the U. S [9]. However, other PFAS compounds continue to replace ones banned and phased out, still posing significant health risks to consumers. The US phased out domestic production of compounds PFOA and PFOS, however, these compounds have been replaced by other PFAS chemicals such as ones included in the GenX and PFBS categories of PFAS, often being shorter chain versions of the former compounds, and still problematic. PFAS have become more and more of a growing health concern as they pose serious health risks, with possible health issues such as organ failure, birth defects, infertility, and cancer. In April of 2024, the EPA announced the final rule for the National Primary Drinking Water Regulation, evaluating six PFAS chemicals and enforcing maximum contaminant levels for each to decrease the PFAS concentrations in water sources [8]. Despite these regulatory advancements, the persistence and widespread use of PFAS continues to pose significant challenges. Ongoing research, stringent regulations, and innovative remediation strategies are crucial to mitigating the impact of PFAS on human and environmental health.

**Biosolids Use**

Biosolids are the byproduct of wastewater treatment. During the treatment of wastewater liquids and solids are separated from each other, each of these phases are then treated and becomes effluent. After the solids have been treated through physical and chemical processes biosolids are produced as nutrient and organic matter semi-solid sludge [1,4]. These biosolids are generally used for three purposes: land application, incineration, and landfilling. The biosolids can be recycled and applied as fertilizer for the use of land applications to improve and maintain soil health and plant growth. Biosolids can promote the growth of crops making them a great resource to be recycled for the use of agricultural purposes. When applied to crops the application rates of biosolids are restricted based on the nutrient needs of the crop as well as the content of the biosolids [3]. A large factor of the application rate is the nitrogen content of the biosolids, nitrogen has very high levels in biosolids, and ensuring that the nitrogen is used and doesn’t become a part of runoff and polluting groundwater as it can cause health concerns is important. Another regulation surrounding the application of biosolids depends on the class of the biosolids. The classification is dependent on how the biosolid has been treated for the removal of pathogens. Class A biosolids are treated until there is no detectable level of pathogens or possible viruses in the biosolids. Class B biosolids are generally treated less and may have a detectable level of pathogens that is still acceptable [2].



**Figure 1.** Biosolids Use & Disposal from 2022 Biosolids Annual Reports [1]

Annual reports of biosolids disposal are taken from over 2,500 large treatment plants every year in the United States. The above figure shows how biosolids were used in 2022, it's important to note that over 50% of biosolids that were disposed of were used for land application. In 2022, Maine banned the use of Biosolids due to concerns surrounding PFAS as high levels of PFAS were found in soil that had biosolids being applied. This application of contaminated biosolids caused large amounts of crops and animal products to be contaminated with biosolids. In 2018 about 40% of Maine’s biosolids that were produced were being applied to soils for agricultural purposes [6]. In 2015 a survey of 580 publicly-owned treatment works in NYS information on their biosolids use was gathered. It was found that over 68% of biosolids were landfilled while 16% were incinerated and another 16% were used for beneficial use [5]. In September of 2023, the NYS DEC prepared a program policy surrounding the use of biosolids recycling and the control of PFAS compounds within them. The NYS DEC continues to support the use of biosolids knowing that biosolids must be used cautiously surrounding possible contaminants. The policy is being currently used until the US EPA issues standards for PFAS in biosolids [7]. Currently, the NYS DEC is working with SUNY ESF to collect and sample biosolids samples from numerous WWTPs located in NYS. They look to use this data to reduce the risks that are associated with using potentially PFAS-contaminated biosolids.

**PFAS in Biosolids**

[Alder et al. 2014](https://www.sciencedirect.com/science/article/abs/pii/S0045653514009060)

This study investigates the presence and levels of PFAAs in digested sewage sludges from 45 wastewater treatment plants across Switzerland. The research identifies significant variability in PFAA concentrations, which is attributed to various industrial activities, such as metal manufacturing, the use of aqueous fire-fighting foam, and landfill leachates. This study highlights the prevalence of PFOS as the dominant PFAA, with concentrations ranging from 4 to 2440 ug/kg. Elevated PFOS levels were particularly observed in areas where there was industrial activity from metal plating industries, AFFF, and landfill. For instance, WWTPs that received effluent from these activities had higher median concentrations of PFAA than those that didn’t. PFOA and various PFCAs were also looked at but had primarily lower concentrations, these were primarily linked to other industries that did not produce as much effluent or were releasing high concentrations of PFAAs into their effluent. The median concentration of PFOA across all WWTPs was notably lower, indicating a reduced affinity for organic carbon and proteins compared to PFOS. The study revealed a decline in PFOS concentration over time which reflects the phasing out of certain PFAAs and replacing them with alternative substances [10].

[Campo et al. 2014](https://www.sciencedirect.com/science/article/abs/pii/S0048969713013399)

This article examines the presence, distribution, and removal efficiency of 21 PFAS in wastewater and dehydrated sludge samples from 16 sewage treatment plants in Spain over two consecutive years, 2010 and 2011. The study revealed that all the samples, except for two sludge samples from the sewage treatment plants, were contaminated with at least one PFAS. PFBA, PFPeA, and PFOS were the most frequently detected compounds. The highest concentration recorded in 2010 was 5.60 ug/L of PFHxA and in 2011 0.31 ug/L of PFBS. In sludge samples, the highest concentrations were 1.79 ug/L of PFOS and 1.88 ug/g dry weight of PFBA. The study found that sewage treatment plants are a focal point of PFAS contamination into other sources with PFAS loads being discharged as part of the effluent and sludge production. The removal efficiencies in sewage treatment plants indicated that PFAS are only partially eliminated, and their distribution coefficients for sludge cannot be directly compared to those for sediment due to different sorption behaviors. The variability in PFAS concentrations was influenced by factors such as compound hydrophobicity, with long-chain PFASs showing higher tendencies to partition into biosolids [11].

[Ghisi et al. 2018](https://www.sciencedirect.com/science/article/pii/S0013935118305577?via%3Dihub)

This paper analyzed the literature on the correlation between the concentration of PFAS in plants and the concentration of PFAS in soil, identifying possible pathways through the food chain where concentrations of PFAS could transfer to humans. It was noted that as water in soil is a large factor in PFAS concentrations, both water and soil concentrations of PFAS correlated with the accumulation of pollutants in plants, with notably higher concentrations found in vegetative parts of the plant. The amount of water that a plant transpires also affects the concentration of PFAS accumulated within the plant. This suggests that all parameters influencing the transpiration of plants will then affect the concentration of PFAS accumulated, including temperature, humidity, and irradiance. An experiment was also reviewed finding that the accumulation of PFAS concentrations in different plants differs; it was found that wheat plants would have higher concentrations than oats which also had higher concentrations of maize. It was also found that bioaccumulation is affected by the substance's chain length and function groups where longer-chained compounds generally have lower accumulation rates and PFSAs would have lower accumulation than PFCAs. Studies on vegetables and fruit accumulation of PFAS were reviewed noting that different plants have different uptake properties for different PFAS and that longer chained substances prefer to accumulate in roots and shorter chain substances accumulate in the leaves and fruits of plants. Most notably, it was revealed that much higher levels of PFAS in plants were found that were grown in biosolids, especially with higher concentrations of PFAS in biosolids that were industrially impacted [12].

[Link et al. 2024](https://pdf.sciencedirectassets.com/271390/1-s2.0-S0304389423X00181/1-s2.0-S0304389423020186/main.pdf?X-Amz-Security-Token=&X-Amz-Algorithm=AWS4-HMAC-SHA256&X-Amz-Date=20240730T003336Z&X-Amz-SignedHeaders=host&X-Amz-Expires=300&X-Amz-Credential=ASIAQ3PHCVTYRAXME7JL/20240730/us-east-1/s3/aws4_request&X-Amz-Signature=8f7a5ada2e87fc7f9933b9f1bfc2873b7062abadf605ecfdf7825080624947dd&hash=2bd5235f11c349c1558a881bb4858116202c5d412e047b241c05cc79bcada130&host=68042c943591013ac2b2430a89b270f6af2c76d8dfd086a07176afe7c76c2c61&pii=S0304389423020186&tid=spdf-f5beafa8-1c08-4f09-a76a-091219cbde48&sid=96be62e75d70504fbf8b5659cfb35fd28daagxrqa&type=client&tsoh=d3d3LnNjaWVuY2VkaXJlY3QuY29t&ua=131c5e0602545253515d&rr=8ab142186dc343e6&cc=us)

This article provides an extensive analysis of PFAS in biosolids from WWTPs across Michigan. This study analyzed 350 biosolids samples from 190 different WWTPs, revealing that PFAS concentrations ranged from 1 to 3200 ng/g, with an average of 108 ng/g dry weight. PFAS with carboxyl and sulfonic functional groups comprised 29% and 71% of total PFAS concentrations. The primary variability in PFAS concentrations was attributed to long-chain PFAS< which has a higher tendency to partition into biosolids, while secondary variability was linked to short-chain carboxylic compounds like PFHxA. The study also found that replacement compounds such as FTSA and PFBS contributed to variability. Sulfonamide precursors were detected at similar or higher concentrations. PFAS enrichment in biosolids generally increases with compound hydrophobicity, with long-chain compounds more likely to partition into biosolids. The study highlighted that PFAS partitioning onto solids in WWTPs is a complex process influenced by multiple factors and not easily described using standard partition coefficients. The study emphasized the potential for PFAS in biosolids to contaminate soils, crops, and water resources through land application, leading to regulatory measures aimed at reducing PFAS loading to agricultural soils. It calls for more comprehensive analysis, including additional PFAS compounds, to improve understanding of PFAS behaviors in biosolids and stresses the need for increasing regulatory docs on sulfonamide compounds due to their potential transformation into PFOS [13].

[Munoz et al. 2022](https://pubs.acs.org/doi/abs/10.1021/acs.est.1c03697)

This study explored the presence of PFAS in 47 organic waste products applied to agricultural fields in France. The research was conducted on sewage sludge, municipal solid waste composts, and livestock manures with a total of 160 PFAS from 42 different classes being detected using different methods. The study found that organic waste products such as pig slurry, poultry manure, and dairy cattle manure, had low levels of PFAS. In contrast residential and industrial wastes, including paper mill sludge, sewage sludge, and household waste composts, exhibited significantly higher PFAS concentrations. Historical municipal biosolids and composts from the late 1900s were dominated by PFOS, and precursor to PFOS. In contemporary urban organic waste products PFOS replacement compounds had higher concentrations with 6:2 FTSA being the most prevalent [14].

Considering the diverse range of studies examining PFAS in biosolids and sludge across various regions a few critical themes emerge. First, the prevalence of PFOS and its replacements indicates that despite efforts to phase out certain PFAS, their legacy persists in the environment and now additional compounds make up the concentrations. This is evident from Alder et al. [10] in Switzerland, where industrial activities significantly influenced PFAS concentrations, and from Munoz et al [14] in France, where contemporary urban waste products still showed high levels of PFOS replacements like 6:2 FTSA. The second critical theme is the variability in PFAS concentrations across different treatment plants and regions, highlighting the influence of local industrial activities and waste management practices. Campo et al. [11] in Spain found that sewage treatment plants are focal points for PFAS contamination, with only partial removal of these substances. Similarly, Link et al. [13] in Michigan emphasized the complexity of PFAS partitioning in WWTPs, influenced by multiple factors, including compound hydrophobicity and the presence of replacement compounds. Third, the potential environmental and health implications of PFAS in biosolids are a recurring concern. The possibility of PFAS transferring from biosolids to agricultural soils, crops, and ultimately the food chain, as explored by Rossella Ghisi et al. [12] underscores the need for stringent regulatory measures. The studies collectively call for more comprehensive analyses of PFAS in biosolids and an increased focus on understanding the behaviors and impacts of both legacy and replacement PFAS compounds.

**Factors Influencing Fate & Transport of PFAS in Biosolids**

[Álvarez-Ruiz et al. 2024](https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4835548)

This paper analyzed soil cores and groundwater at a site where biosolids have been applied for 38 years to understand the fate and transport of PFAS. It was found that the total PFAS concentrations in the soil would decrease from depth, where the topsoil was primarily long-chain PFAAs and increased depths increased the concentration of short-chain PFAAs. The distribution of PFAS in soil concerning depth was correlated with chain length and dependent on the high organic carbon content of the surface soil. The higher organic carbon content was due to many years of biosolids being applied which minimized the leaching of long-chain PFAS, as the organic carbon content decreased with depth so did the total concentration of PFAS. This is due to the hydrophobicity of fluorinated alkyl tails which promote interaction with organic carbon and increases with increasing chain length. Within the top layers of soil, it was found that PFOA and PFOS were the most abundant PFAS making up around half of the total PFAS concentration. Despite after four decades of biosolids use on the land it was found that the surrounding wells had limited PFAS concentrations that did not exceed the EPA’s drinking water standard for PFOA [15].

[Behnami et al. 2024](https://www.sciencedirect.com/science/article/pii/S0048969724017005?via%3Dihub)

This paper summarizes recent literature about PFAS occurrence and transformation in WWTPs and calls on the need for research to be done on the transformation of PFAS in biosolids and the possible infiltration of PFAS into the food chain and water sources. The paper found that despite different treatment procedures, similar PFAS concentrations can be found in biosolids produced by different WWTPs. The partitioning between the aqueous and solid phases in the creation of biosolids as well as the sludge retention time play a role in influencing PFAS concentrations and accumulation. It has also been shown that aerobic bacteria can transform PFAS compounds influenced by microorganisms that utilize defluorination. As well treatment methods can affect PFAS sorption or , finding that functional groups and size of the molecule can influence the sorption. As well mono and divalent cations can influence the value and pH has a role in partitioning PFAS. It was observed that for lower pHs there was an increase in sorption and higher pHs had differing effects which was dependent on the PFAS compound and sediments. The carbon chain length of a PFAS compound significantly affects the compounds partitioning where longer-chain compounds sorb more and shorter-chain compounds sorb less. Also protein content can influence the adsorption of PFAS with higher amounts of proteins increasing it, and divalent cations such as calcium and magnesium can increase adsorption whereas monovalent cations such as sodium can decrease adsorption [16].

[Pepper et al. 2021](https://www.sciencedirect.com/science/article/pii/S004896972103521X?via%3Dihub)

This paper evaluated the impact of PFAS on soil and leaching into groundwater from the land application of biosolids through a field study implemented in the Arizona communities of Pima and Pinal counties where long-term land application of biosolids has occurred. The soils were sampled from five different sites with a distinct history of agricultural activity and application of biosolids, the soils were primarily arid with textures consisting of sandy loams, clay loams, and clay. The soil's organic matter levels were all low less than 1% and had pHs of 8. This study found that within the biosolids applied PFOS was at the highest concentration It was found that after a long period of biosolids application, the concentration of PFAS in soils that received the biosolids was relatively low, suggesting that the possibility for groundwater contamination is relatively low, considering factors such as the depth of groundwater, low rates of precipitation, and high rates of evapotranspiration within Arizona. The potential for leaching of PFAS is enhanced with irrigated agriculture in arid regions where large amounts of irrigation water are consistently applied. Despite this, minimal movement of PFAS was observed [17].

[Sepulvado et al. 2011](https://pubmed.ncbi.nlm.nih.gov/21446724/)

This document presents a detailed study on the behavior of PFAS in soil after the application of municipal biosolids. The research aimed to investigate the occurrence and fate of PFAS in agricultural soils amended with municipal biosolids, considering aspects such as concentration levels, mass balance, desorption, and transport. The study involved collecting biosolids and soil samples from various sites and analyzing them for different PFAS using advanced laboratory techniques such as liquid chromatography and tandem mass spectrometry. For the PFAS levels in biosolids and soils, they found that PFOS was the most dominant PFAS in biosolids and soils, with concentrations that were influenced by the amount of biosolids used or their loading rate. They found linear relationships between biosolids loading rates and soil concentrations of PFAS, indicating a predictable accumulation of PFAS in soils based on the loading rate and concentration of PFAS in biosolids. Desorption experiments showed that the potential for PFAS to leach into groundwater varies by chain length, with shorter-chain PFAS displaying higher leaching potential. The research suggested discrepancies in previously used models for predicting desorption behaviors, highlighting the need for specific evaluations under actual field conditions. Although no soil concentrations tested exceeded the EPA’s residential soil screening values, the potential for groundwater contamination remains a concern due to leaching, especially under equilibrium conditions that were modeled in the study [18].

[Silva et. al, 2022](https://www.pc-progress.com/Documents/Jirka/Silva_et_al_JCH_2022.pdf)

These articles employed the use of a model titled HYDRUS to quantify the leaching and transport behavior of PFAS from biosolids in agricultural fields to groundwater using numerical modeling, focusing on simulating realistic conditions at two central Illinois test sites. Key compounds PFOA and PFOS were modeled, these specific PFAS vary in chain length and properties, influencing their interactions with environmental conditions differently. The model ran over a simulated period of 150 years post biosolids application, intended to observe the long-term fate of PFAS. They found that soil sorption/desorption dynamics predominantly govern PFAS mobility, with different PFAS showing varied rates of movement through soil based on their molecular characteristics. Despite the potential for Air-Water-Interface adsorption to affect PFAS movement, this was found to be minimal, particularly within the biosolids-amended surface soil. It was observed that more hydrophobic PFAS, such as PFOS, moved slower compared to shorter-chain PFAS due to stronger soil interactions. The simulation provided an empirical relationship that predicted PFAS concentrations at the saturated zone based on biosolids application rates and characteristics, helping forecast long-term impacts on groundwater. Different soil textures at the test sites influenced PFAS transport. Homogenous silty sand soils at one site facilitated somewhat faster PFAS movement compared to more heterogeneous soils at the other site, which retained moisture and PFAS longer. This study suggests that there needs to be an amount of safety and regulations regarding the application of biosolids with regard to PFAS concentrations. It also suggests that further research needs to be done on the degradation of PFAS precursors [19].

[Arcadis U.S., Inc. 2020](https://www.ncasi.org/resource/review-of-models-for-evaluating-per-and-polyfluoroalkyl-substances-in-land-applied-residuals-and-biosolids/)

This review examines and summarizes the factors that affect the fate and transport of groundwater leaching, surface water runoff, and plant uptake of PFAS. They evaluate the following factors and the parameters that affect leaching:

|  |  |  |  |
| --- | --- | --- | --- |
| Mechanism | Description | Parameters | Impact |
| Recharge and Advection | Precipitation/irrigation percolates from the surface and carries PFAS through the vadose zone to groundwater. | - Soil permeability  - Water saturation | High |
| Dispersion and Diffusion | Dispersion and diffusion of PFAS constituents in water | - Overall water content  - Pore size distribution | Moderate to minor |
| Hydrophobic Sorption (Koc) | Interactions between PFAS and soil. | - Adsorption-desorption Distribution coefficient (Kd)  - Soil composition (e.g., clay content)  - Organic carbon  - Particle surface area | High |
| Air-Water Interface Partitioning (Kia) | Alignment of PFAS at interfaces between porewater and air, with perfluoroalkyl tails in the air phase and their ionic functional groups in the water phase. | - Porosity  - Water saturation  - PFAS chain length | Moderate to high |
| Electrostatic Adsorption | Bonds between negatively and positively charged constituents or their polar ends with oppositely charged ions in soils | - Negatively charged clays in the soil  - PFAS molecular structure | Moderate |
| Surfactant Induced Flow | PFAS reducing surface tension of the water-air-soil interface and causing vertical pore water flow | - PFAS Concentration  - Water saturation | Moderate to low |
| Volatilization | Chemical volatility of some constituent, relevant for precursors to PFAAs | - Henry’s Constant, Kh  - Interconnected unsaturated pore space | Low |
| Degradation | Biotic or abiotic degradation, relevant for precursors to PFAAs | - Microbial communities | Low to none |

**Table 1.** Factors that affect leaching of PFAS [24]

The fate, transport, and biotransformation of PFAS in biosolids are influenced by a number of factors. Organic carbon content in the biosolids and soils plays a significant role, with high levels in the surface of soil due to biosolids application reducing the leaching of long-chain PFAS due to their hydrophobic interactions with organic carbon [15]. The partitioning behavior of PFAS is influenced by their chain length is crucial to understand as longer chain PFAS tend to sorb more to solids, while shorter-chain PFAS have higher mobility and thus experience more leaching [16]. Environmental conditions such as soil pH, presence of cations, and protein content also impacts the PFAS sorption and transport. Where lower pH increases sorption and cations like calcium and magnesium enhance PFAS adsorption [16]. Soil texture affects PFAS movement, with heterogeneous soils retaining more PFAS compared to homogenous silty sands which facilitate faster movement [19]. Additionally, climatic conditions, such as low precipitation in agricultural settings can enhance it [17]. Finally, microbial activity can transform PFAS compounds, and treatment methods at wastewater treatment plants influence the overall PFAS concentration and partitioning in biosolids [16]. These factors collectively influence PFAS leaching from biosolids. However, more research needs to be done to better understand and model how these factors accurately affect the leaching process.

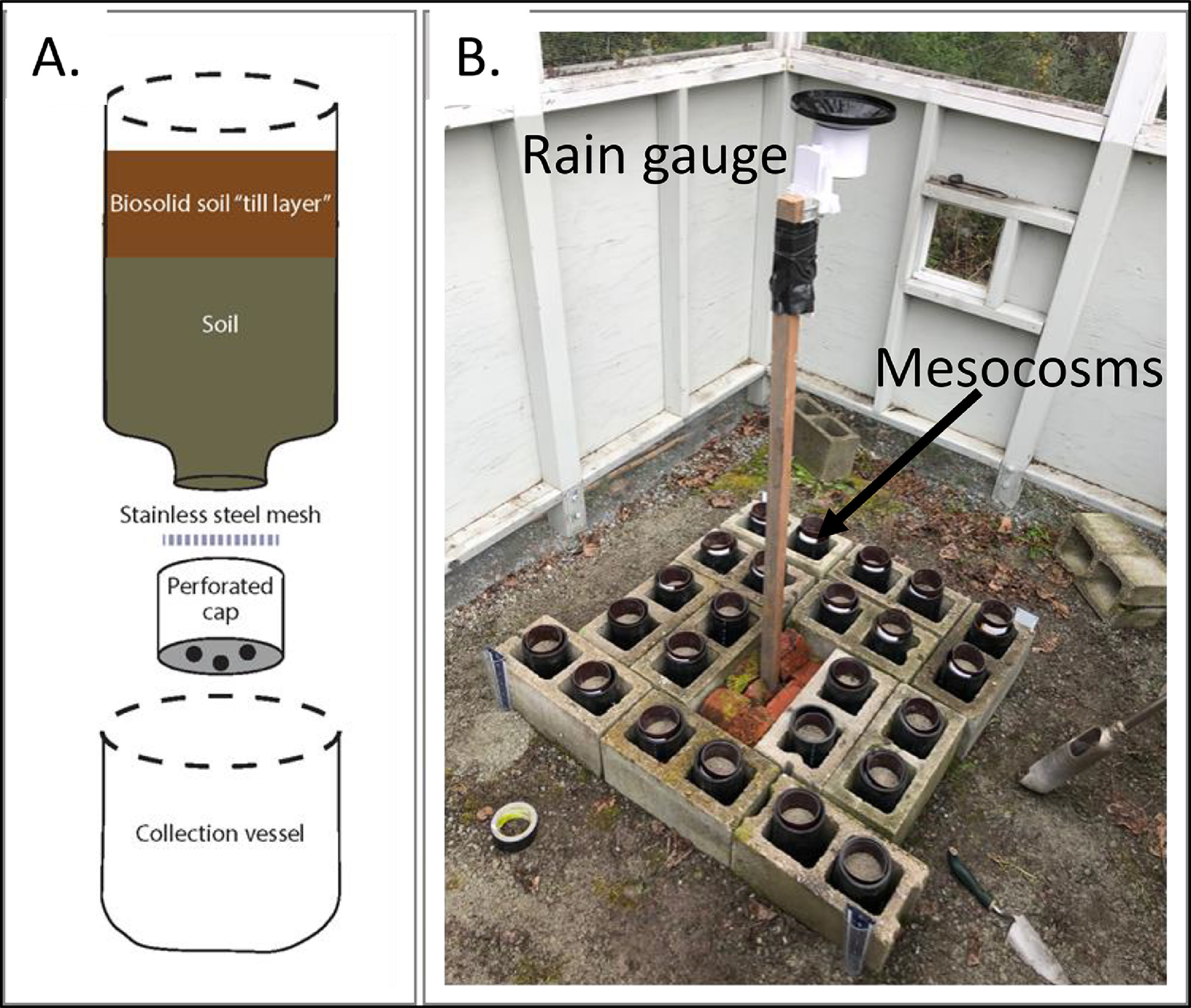
**Experimental Setups**

[Holly et al. 2024](https://pubs.acs.org/doi/10.1021/acsestwater.3c00414)

This article investigated the leaching potential of PFAS from biosolids and evaluated the efficacy of biochar in mitigating PFAS leaching. The study was conducted through undisturbed soil column trials using samples from four regions in Wisconsin, simulating annual precipitation with synthetic rainfall. The treatments included control columns, soil amended with biosolids, and soil receiving a mixture of biosolids and biochar. Results showed that PFAS concentrations in leachate were significantly affected by soil location and site history. In three locations, PFAS concentrations in leachate exceeded the local groundwater standard for combined PFOA and PFOS concentrations. This indicates that even a one-time application of biosolids can lead to groundwater contamination, posing a long-term risk to human health. Furthermore, biochar was found to significantly reduce PFAS leaching, particularly for higher chain length PFAS, with reductions ranging from 40-64% in total PFAS. This suggests that biochar could facilitate the sustainable use of biosolids by mitigating the leaching of long-chain PFAS, although further long-term field evaluations are necessary [20].

[Schaefer et al. 2022](https://www.sciencedirect.com/science/article/abs/pii/S004313542200361X)

This article investigated the release and leaching behavior of PFAS from biosolids applied to soil using mesocosm experiments. The study involved collecting finished biosolids from seven municipal water resource recovery facilities across the United States and analyzing them for 54 PFAS compounds. The total PFAS concentrations in the biosolids ranged from 323 to 1100 ug/kg dry weight, with over 75% of the PFAS fluorine mass associated with precursors, particularly diPAPs. Outdoor mesocosm column experiments were conducted to simulate biosolids land application and assess PFAS leaching over six months. The results showed sustained PFAS leaching, with PFAA concentrations in the leachate ranging from tens to hundreds of ng/L. Notably, the total mass of PFAAs leached exceeded the initial mass present in biosolids, indicating a significant transformation of PFAS precursors to PFAAs during the leaching process. The study found that while the total oxidizable precursor assay generally underpredicted the fluorine content of precursors, the transformation of diPAPs and other precursors contributed substantially to the observed PFAS leaching [21].

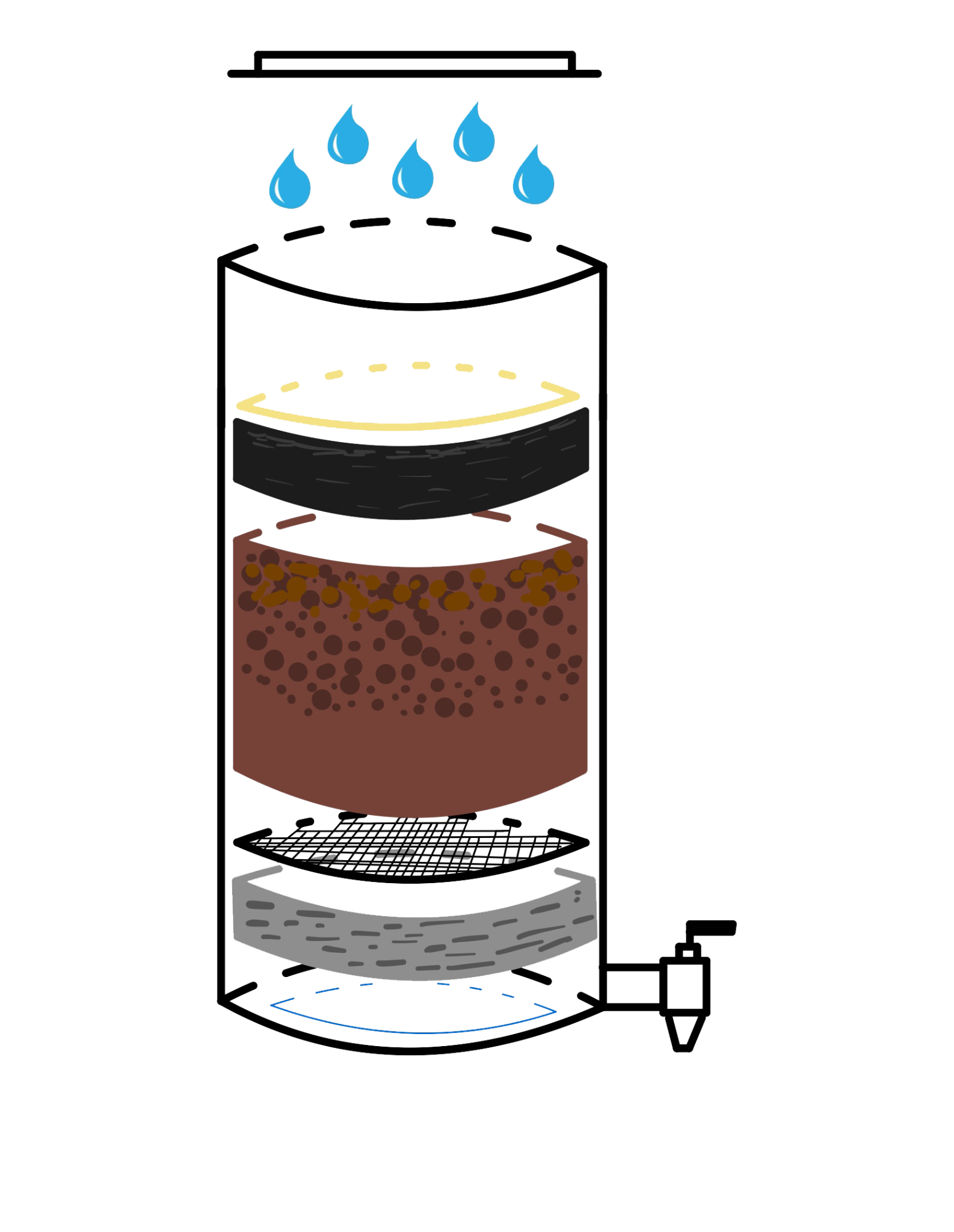


**Figure 2.** Experimental Setup [21]

[Glubt et al. 2021](https://www.sciencedirect.com/science/article/pii/S0269749120366069?via%3Dihub)

This paper examined the consistency of two different experimental setups used to measure solid-phase sorption of coefficients and isotherms of PFAS. Evaluating close to 100 papers from the previous 15 years, the team found an overwhelming preference for batch experiments over column experiments. Some studies found differences in results from the methods, but they argue these stem from artifacts employed in the experiment implementation, suggesting that the methods may not be inconsistent due to errors. They carried out their own batch and column experiments for the sorption of PFOS and PFOA, using 3 different media and a range of influent representative concentrations, which many past experiments did not do, finding consistent results overall 4 PFAS-media systems employed. Even in the presence of rate-limited and nonlinear sorption, results can be consistent as long as appropriate experimental conditions are applied. They go further in suggesting that, although both methods have their benefits, column experiments offer significant advantages, as they can be implemented with dynamic representative conditions, minimize soil abrasion, and use higher soil-to-solution ratios than batch systems, allowing more realistic conditions. This comes with limitations such as a longer timeframe and increased workload, but these can be overcome by using cosolvent solutions and a modified miscible-displacement column method. They conclude that while both methods can be reliable and useful, column experiments, in spite of their challenges, can allow studies to create more realistic field conditions, and used in conjunction with batch experiments can allow for a better understanding of sorption processes [22].

Looking at the experimental setups that previous research have been conducted on the leaching of PFAS from biosolids, a similar experiment can be formulated to continue to research the properties that lead to leaching.



**Figure 3.** Schematic for PFAS Leaching Experiment

The design consists of an HDPE bottle that then has stacked layers of a mixture of gravel, stainless steel wire mesh, soil, biosolids, and filter paper. Rainfall will then be simulated by pumping small amounts of water over time into the container to simulate leaching. The leached water will then be collected through a collection valve that is put at the bottom of the container. This leachate will then be tested for PFAS using mass spectrometry. The amount of rainfall that is being simulated will follow the amount of water that corn receives in a year which is 22 to 30 inches per year [23]. To simulate realistic biosolids application the amount of biosolids that will be applied to the soil will depend on the amount of nitrogen content within the biosolids, using corn as the example crop the amount of biosolids that are applied is 140 lb/acre which when converted to g/cm^2 is 0.00156919 g/cm^2 for biosolids containing 4-5% nitrogen content.

**Potential Remedies**

[Sørmo et al. 2020](https://www.sciencedirect.com/science/article/pii/S0048969720375653?via%3Dihub#f0015)

This paper reviewed the use of woody residues like waste timber as an effective sorbent for the remediation of PFAS-contaminated oil in the form of biochar. They found that biochar made out of waste timber could be used to effectively reduce the leaching of PFAS from contaminated soil and that the effect is improved by using activated biochar that is produced optimally at a specific temperature of 900℃. It was also found that for differing sites that had different soil properties different types of activated biochar were better or worse at sorption, for example, sorption was found to be weaker in higher total organic carbon soil compared to low total organic carbon soil. As well it was found that weaker sorption was observed for short-chain PFAS when compared to longer-chain PFAS sorption. These ideas suggest that the assessment of soil properties to then produce a specific type of biochar to remediate a site will have to be taken into account for higher efficiency [25].

[Hakeem](https://www.sciencedirect.com/science/article/pii/S1385894724040245?fr=RR-2&rr=88e83e5ea9130f8f) et al. 2024

This paper reviewed recent literature on the fate and transformation of PFAS in the thermal treatment of biosolids. They found that there is a large amount of evidence that thermal treatments such as incineration, pyrolysis, and gasification can both remove and destroy PFAS found in biosolids. Many thermal treatments were found to report more than 90% removal of PFAS. The destruction and volatilization of PFAS were found to occur at a range of temperatures above 500℃ with there being a substantial removal of PFAS from their original substance and into gas or liquid effluent as well as the possibility of the destruction or mineralization of the compounds which would occur at much higher temperatures and completely defluorinate the compounds [26].

Possible remedies that could mitigate PFAS concentrations are using biochar to sorb the PFAS as well as thermal treatment to destroy the PFAS. Burning organic matter at high temperatures can produce biochar that due to its high surface area has high sorbing of PFAS concentrations. Mixing this in with biosolids seemed to work well as a way to significantly reduce PFAS leaching [20]. However, the biochar’s sorbing properties depends on the organic matter that it is made out of, it was observed that specific materials turned into biochar exhibit different sorbing properties, so creating a biochar to sorb PFAS would require taking into account the biosolids and soil properties for each specific site they are being applied to [25]. The use of thermal treatment as a way to destroy PFAS in biosolids is a promising way to completely remove PFAS from biosolids and stop the continued movement of PFAS into potential contaminating pathways. However, the thermal treatments require very high temperatures to be able to destroy the PFAS [26] making it incredibly difficult to destroy it and leading to the production of carbon dioxide.

**Conclusion**

The assessment of environmental factors impacting the biotransformation of PFAS in recycled biosolids reveals the complexity and persistence of these contaminants. Despite regulatory advancement and ongoing research efforts, PFAS continue to pose significant challenges due to their resistance to degradation and their widespread presence in various environmental matrices. The studies reviewed highlighted several critical points regarded PFAS in biosolids. The first is that PFAS, particularly the legacy compounds like PFOS and their replacements remain persistent in biosolids and sludge samples. Despite efforts to phase out certain PFAS, replacements continue to contribute to contamination across many regions due to residential and industrial activities. The second is that concentrations of PFAS in biosolids varies significantly across different WWTPs and regions. This variability is influenced by local industrial activities, waste management practices, and treatment methods. As different WWTPs receive different influent that they treat biosolids from different WWTPs end up having varying PFAS concentrations. Third is the potential for PFAS to transfer from biosolids into the food chain. As PFAS from biosolids can leach into groundwater or transpire into plants there is growing concern for PFAS being in drinking water sources or products from agricultural activities. The long-term application of biosolids can lead to the accumulation of PFAS in soils, posing risks to contaminating the environment and affecting human health. Fourth, there are several factors that influence the fate and transport of PFAS in biosolids, these include but are not limited to soil properties, organic carbon content, AWI, environmental conditions, such as pH, the presence of cations, and the structure of PFAS. Understanding these factors is crucial for predicting PFAS behavior and implementing effective mitigation strategies. Regarding next steps to continue to learn about PFAS in biosolids are to continue to do research on understanding the fate, transport, and biotransformation of PFAS in biosolids through the use of experimental setups. For potential mitigation strategies the use of biochar and thermal treatments show promise in reducing PFAS concentrations in biosolids. However, the efficacy of these methods depends on specific site conditions and characteristics of the biosolids and soil. Addressing the challenges posed by PFAS in recycled biosolids requires a multifaceted approach involving comprehensive research, large sampling, stringent regulations, and innovative remediation strategies. Continued efforts to understand the behavior of PFAS in the environment and to develop effective mitigation techniques are crucial for protecting human health and the environment from the persistent threat of PFAS contamination in biosolids.

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