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Grant Information: Institution, Principal Investigator(s), Contact Information, Grant Number	**Yale University** **Project:** Understanding and Enhancing PFAS Phytoremediation Mechanisms Using Novel Nanomaterials **Project Leaders**: Vasilis Vasiliou, Christy Haynes (University of Minnesota), Jason White (Connecticut Agricultural Experiment Station) **Funding Period:** 2021-2025
Technology	We will design and synthesize novel nanomaterials, such as ultraporous mesostructured silica nanoparticles (UMNs) and carbon dots with a tunable surface chemistry that have increased affinity for recalcitrant per- and polyfluoroalkyl substances (PFAS). These two nanomaterials are known to be accumulated by plants and effectively enhance PFAS uptake and translocation from water and soil into plants as a novel phytoremediation strategy.
Innovation	**Materials:** We have developed carbon dots (CDs) and ultraporous mesostructured silica nanoparticles (UMNs) with an affinity for a range of specific PFAS using sustainable precursors. CDs are synthesized with amine-rich precursors, such as chitosan and polyethyleneimine (PEI), to target a range of surface charges and nanoparticle size with high PFAS affinity and enhanced potential for plant uptake. Similarly, the UMNs are modified with different functional groups to target specific PFAS to significantly promote phytoextraction by plants. **Biological:** We are exploring the use of hemp *(Cannabis sativa)* and zucchini *(Cucurbita pepo)* as phytoremediation species. **Why is this technology/approach different than what is already in the market?** PFAS PFAS are a large and complex group of highly toxic organic pollutants that are resistant to degradation in the environment; some analytes are more mobile and can contaminant groundwater, whereas others are less mobile but exceedingly persistent in soil. Therefore, novel and effective remediation/cleanup technologies of PFAS are urgently needed. We are focused on a sustainable remediation approach known as phytoremediation (i.e., using plants to extract recalcitrant PFAS from soil). We hypothesize that novel nanomaterials such as UMNs and CDs can be used to enhance the mobility and accumulation of PFAS into plants. The luminescent properties of these novel materials will allow us to visually track both PFAS sorption to the particles, as well as movement of the nanoparticle-PFAS complex into and throughout the plants, thus providing critical mechanistic information about our phytoremediation system. The nanomaterials developed in this project will advance phytoremediation as an economical and sustainable technique for removing a wide range of PFAS from soil. In addition, findings from this project will result in a better understanding of how novel nanomaterials (NNMs) can be used to mobilize contaminants in plant-soil systems. This information can be translated to optimize phytoremediation processes with other plant species, contaminant classes, and nanomaterials.

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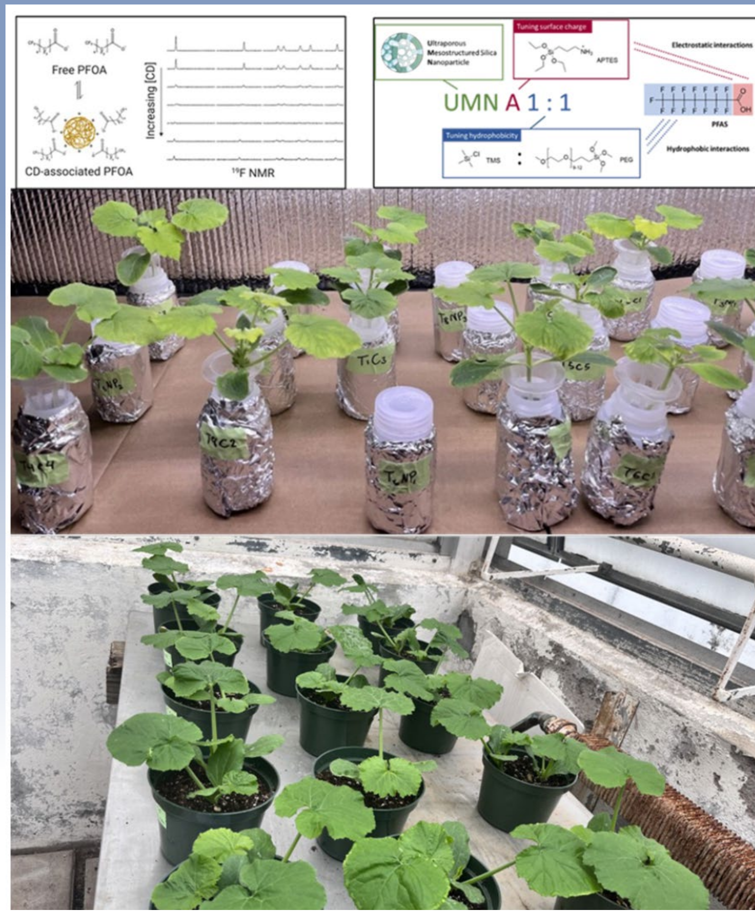
Contaminant and Media	**Contaminants:** Examples include groundwater, drinking water, soil, and sediment. **Media:** The contaminants we are targeting are the 25 PFAS that are most prevalent in soil and water.
Expansion Potential	**Looking Forward: What other contaminants/media would work for your technology?** Our technology could be potentially adapted to other hydrophobic organic contaminants, such as pharmaceutical and personal care products, pesticides, and micro-nanoplastics, as well as toxic elements in soil that may not be prone to plant uptake, such as Pb. It is the ability to tune the surface chemistry of our nanomaterials that enables this platform to be applicable to a wide range of other environmental contaminants. Nano-enhanced phytoremediation strategies could be designed for soil, groundwater, and aquatic systems. For our current PFAS work, we are focused on phytoextraction; once the contaminant is out of the environment and in the plant tissues, disposal and other remediation technologies become easier. We are currently working in conjunction with two other technologies. **Combined Remedy: Would this technology work well with other treatment approaches?** We are working on the combination approaches, mainly: 1) phytoremediation and hydrothermal liquefaction (HTL) and 2) phytoremediation and biodegradation.



Novel sustainable nanomaterials, such as carbon dots and ultra mesoporous silica, are being designed to bind to recalcitrant PFAS molecules in hydroponic and soil systems to promote plant uptake as a nanotechnology-enabled phytoremediation strategy.

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Sites/Samples	We don't have any record of sites in our databases. Loring Air Force Base, Maine.
Technology Readiness Level	TRL 3 — Experimental proof of concept (We are in the process of moving to TRL 4 and will do so within the next six to nine months.)
Update of Progress	UMNs: PFAS uptake experiments with UMNs show that tuning the surface charge of UMNs has a larger effect on PFAS removal efficiency in abiotic systems than tuning the hydrophobicity, and that positively charged UMNs have higher PFAS removal efficiency than the negatively charged UMNs (with percent recovery of 20% compared to nearly 100%). When incubated with multiple PFAS, UMNs show greater removal efficiency for longer chain and more hydrophobic PFAS. Plant uptake experiments with UMNs show a strong trend of increasing bioconcentration factors of PFOA with the treatment of UMNs, although our first experiment in this space did not achieve statistically significant enhancement. Further investigation of UMN effects on PFAS uptake by plants is currently underway. CDs: We are developing various carbon dot nanoparticles (CDs) to enhance plant uptake of PFAS in phytoremediation systems. CDs are synthesized to promote efficient PFAS loading and complexation; the CDs will then act as a carrier for PFAS into plant above-ground tissue. To promote electrostatic interactions between CDs and anionic PFAS, we have synthesized CDs with a positive surface charge using amine-rich precursors, such as chitosan and polyethyleneimine (PEI). We have developed 19F NMR techniques to probe the interactions occurring between CDs and PFAS that allow us to establish binding isotherms, extract Kd values, and thus rank affinity across different CDs and PFAS species. Results to date indicate that PEI-based CDs have the highest affinity for PFAS out of all the CD formulations considered; however, all show PFAS affinity. NMR spectral analysis indicates slow chemical exchange between PFAS and CDs, indicative of a high affinity interaction. The presence of PFAS does not induce any changes to the inherent CD fluorescent properties, which allows us to track CD localization within plants. Additionally, the capacity of CDs to promote PFAS uptake in plants has been studied hydroponically by exposing the plant to PFAS mixture with and without CDs.