Project Description:
Perfluoroalkyl and polyfluoroalkyl substances (PFAS) are a family of toxic, carcinogenic, and bioaccumulating chemicals that are ubiquitous in consumer products, from cleaning chemicals to flame- and stain-retardant treatments of furniture fabrics and carpet. Thousands of small cleaning businesses in the United States routinely create and release hundreds of gallons of PFAS-contaminated wastewater daily from their cleaning operations into the environment due to cleaning products that contain PFAS and/or PFAS in the materials that they clean. Many of these businesses lack an awareness of PFAS presence in their wastewater. Although PFAS are regulated by federal and state agencies, there is no robust tracking or testing infrastructure for identifying sources of PFAS-contaminated water that are released into municipal wastewater streams or private septic systems nor are there products that small businesses can use to filter PFAS from their wastewater prior to disposal. Our state's Department of Environmental Services seeks a low-cost, open-source solution for PFAS filtering and discharge of wastewater created by cleaning operations, and sponsored a capstone project at our school of engineering.

Our innovation lies in the design, prototyping, and testing of a low-cost system for removal of PFAS compounds from wastewater generated by cleaning companies. Our design is rooted in the scientific literature and scales designs from both lab-scale and municipal-scale PFAS filtering studies to provide a small-scale filter solution meeting the requirements of small businesses.

Our system consists of materials and components that can be purchased from retail suppliers to fabricate filters from bituminous Granulated Activated Carbon (GAC), which we identify in the literature as being an effective and inexpensive means of PFAS adsorption from water. We create a set of system requirements for our design by careful review of the scientific literature, which addresses the efficacy of GAC filtering of PFAS, the lifetime of the filtering material, and necessary dwell times of contaminated water in GAC to adsorb greater than 99% PFAS. Based on these requirements, we generate a set of specifications for a multistage, continuous flow GAC filtering system, including flow rate, contact time of contaminated water with filter media, and cost specifications.

Table 1 Design Requirements for an open-source PFAS filtering system

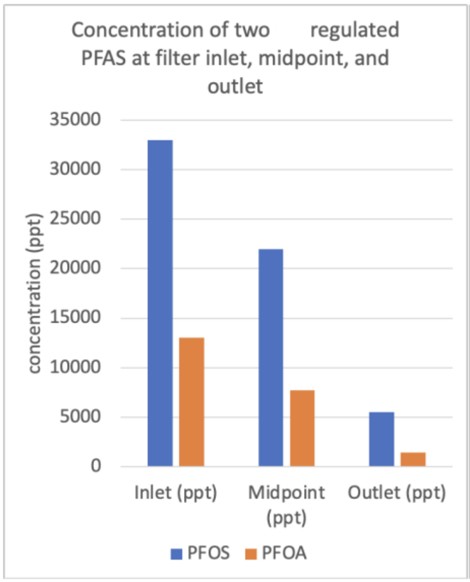
Requirement	Quantification	Justification	Test
Gallons per day filtered	750 gallons/day minimum	Customer requirement, trade publication	Calculation of volume filtered over fixed time interval
PFAS removal efficacy	Within NH regulations for drinking water (reach goal of < 2 ppt, where 2 ppt is the detectable limit)	Existing SOA for AC filters	Test PFAS contaminated water before and after filtering
Cost	Capital cost<$2500 Operation cost <$2000 annually	Must be acceptable to small business to promote adoption	Acceptable environmental fee on customer bill as a cost recovery model
Floorspace required	< 50 sf	Must fit within existing workspace	User and sponsor feedback
Energy use	< 10 kWh per day	Energy costs must be minimal	Pump specs and time of operation calculation
User experience (time, space, ease of use)	Must fit within existing workflow	Must be easy to use and easy to construct from open-source documents provided.	User and sponsor feedback in response to video of use.
Initial PFAS concentration range	Up to 150,000 ppt	Sponsor measurement 118,000 ppt at one site	Obtain 118,000+ ppt wastewater and sample pre- and post-filtering. Send to Eurofins lab for testing.
Life of filter/ time between filter change	3-6 months	Typical for household applications. Needed to minimize cost. Need user feedback to confirm.	No physical test possible as large quantities (> 50,000 gallons of PFAS contaminated water needed). Rely on research to provide a conservative estimate of filter life
Safety	Must be safe to use and leak free, with no potential overflow. GAC absorbs oxygen when wet, so space needs adequate ventilation	Cannot cause more harm to the users or the environment	Calculate potential quantity of O2 absorbed by quantity of GAC used. Assure adequate air volume in space.
Ethical	Educate users. Accessible guides for do-it-yourself construction and use.	All Engineering products must remain consistent with ethical considerations	Users can identify importance of filtering based on educational materials and DIY instructions

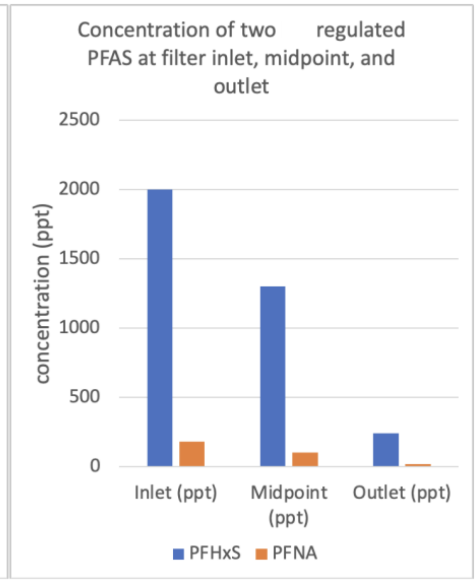
We performed shakedown testing and preparation of the GAC for our system by first filtering 40-50 gallons of tap water through the system followed by 40 gallons of deionized (DI) water. We were unable to acquire PFAS contaminated water until early winter term. We collected approximately 25 gallons of wastewater from a local cleaning business as recommended by our sponsor. Prior to filtering the water, we processed an additional 40 gallons of DI water through the system and collected samples at the inlet and outlet in vials provided by a commercial laboratory recommended by our sponsor and selected for testing. Testing of DI water provides a baseline minimum threshold of PFAS measurable. We then filtered PFAS-contaminated water through the filter collecting samples at the inlet, midpoint (after three spin-down sediment filters and one disposable 25-micron sediment filter, and two cylinders or 2.76 gallons of GAC), and outlet (after an additional, 4.14 gallons of GAC) collecting water samples after approximately half of the PFAS-contaminated water was filtered. The flow rate was set using the outlet valve at approximately 0.5 gallons/minute measured using a stopwatch and five-gallon bucket.

This experiment provides a total BV of 6.9 gallons and a EBCT of = 6.9/.5 or 13.8 minutes exceeding the 10-minute minimum EBCT. Commercial laboratories test water for PFAS according to standards created by the EPA (EPA, n.d.). EPA standard 537.1 is used by the commercial lab that performed our tests. This standard uses solid phase extraction
and liquid chromatography and tandem mass spectrometry to measure PFAS concentrations in drinking water. No such standards exist for wastewater testing, and the common practice for evaluating PFAS in wastewater and that used by the commercial lab to evaluate our samples, is to

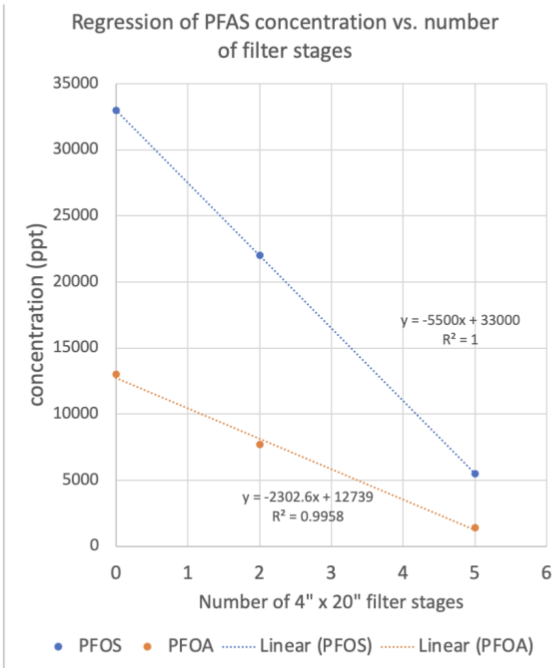
dilute each sample using deionized water by an amount needed to obtain a sample with concentration sufficiently low to test using the drinking water standard, and then report results for the original sample. The commercial lab diluted each sample using a dilution factor specific to the PFAS compound and concentration of the sample.

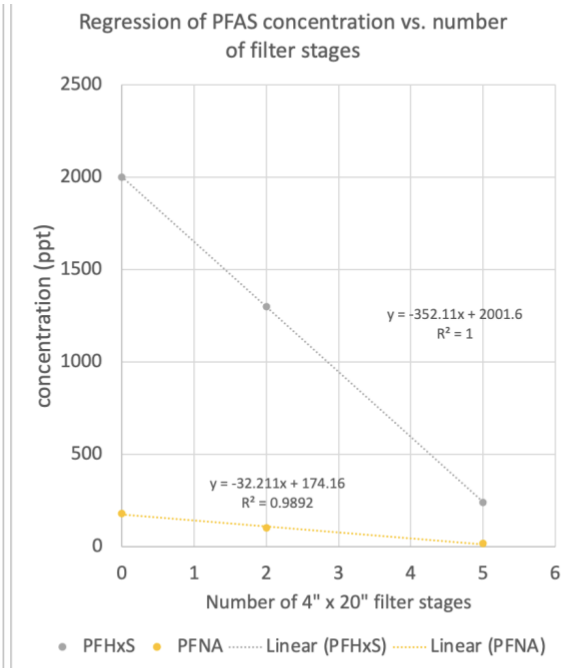
We produced bar charts of PFAS substances present in the samples that are regulated in drinking water in our state – PFOS, PFOA, PFHxS, and PFNA. Of note is that PFOS and PFOA are present in very high concentrations – exceeding 10000 ppt in the samples collected from the local cleaning business wastewater. Each filter stage reduces the PFAS concentration, although after the two filter stages (5 GAC cylinders), no substance was reduced below the state limits for drinking water.



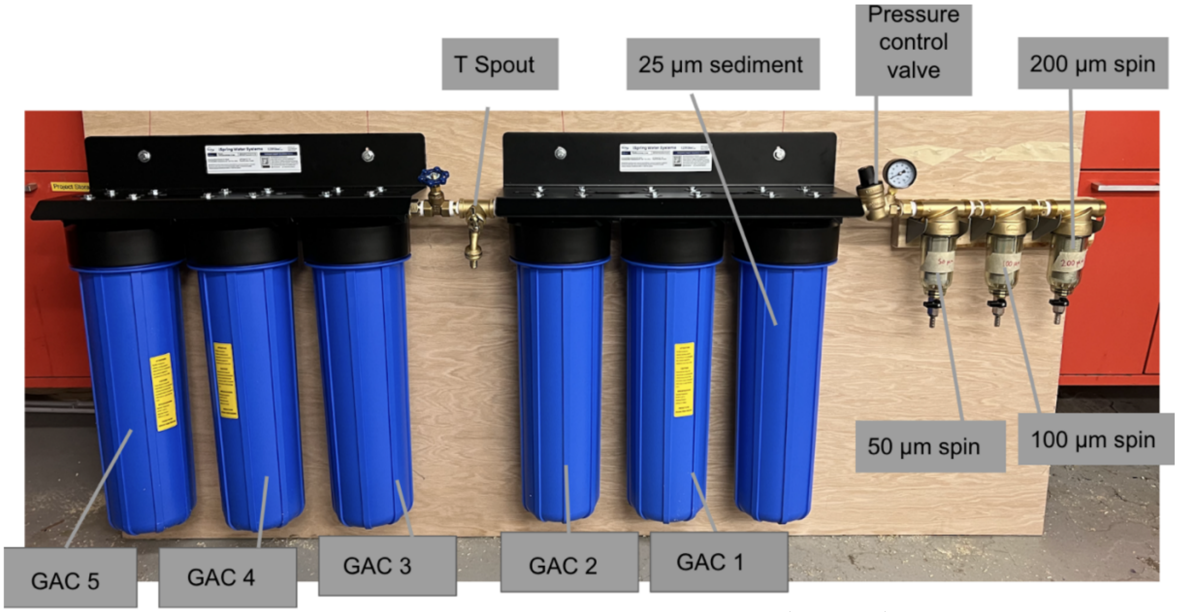


We created a chart to show these results as a function of number of individual filter cylinders, each containing 1.38 gallons of GAC, i.e., inlet, two filter cylinders, and five filter cylinders. The concentration as a function of the number of filter cylinders follows a linear relation as evidenced by a linear regression for each substance, where R-values exceed 0.989 for each substance. These results suggest that additional GAC cylinders have the potential to further reduce PFAS concentrations.





The prototype system we developed is shown below. The filter (right to left) has three spin-down sediment filters followed by a 25 micron sediment filter and five GAC cylinders. We include a T-spout between the two filter sections to measure PFAS concentrations at the midpoint of the filter. We assume that the business owner has a tank to collect contaminated water from cleaning operations, since they currently dispose of the water in a sewer or septic system. After the daily jobs are completed, the full tank is returned to the owner's facility, where it is emptied via pumping into a wastewater holding tank for processing. Our system pump delivers the water to the filter at a rate of 0.5-0.6 gallons per minute providing a EBCT of just over 10 minutes. The water exits the second stage (6th cylinder) and is emptied into a drain to the sewer or septic system. The system processes the water overnight and into the next workday, and the pump stops automatically through an integrated float-switch. For the maximum wastewater volume of 750 gallons, the system operates for 21 hours, processing all wastewater prior to receipt of new wastewater at the end of the next business day.



We anticipate that the cost of the device and its maintenance can be accommodated by small businesses by including a small environmental fee on the customer's bill - much like tire retailers charge customers for disposal of old tires. Lifetime evaluation of the GAC material is needed to complete testing, which requires filtering hundreds of gallons of PFAS-contaminated water. Our final prototype is expected to reduce PFAS concentration to levels safe for release into wastewater streams. Successful development of an open-source, inexpensive PFAS filtering system for small cleaning businesses will reduce PFAS in the wastewater stream thus reducing environmental and health consequences of these toxic chemicals.

Collaboration of faculty, students, and licensed professional engineers:
We met weekly with our engineering technical adviser who is a licensed PE and is a faculty member at our college's school of engineering. We also met biweekly with our co-advisor who is a PFAS expert in the department of epidemiology at our college's medical school. We met biweekly in a mix of zoom and in-person meetings with our project's sponsor who is a research scientist with an expertise in PFAS remediation who is employed by our state's Department of Environmental Services (DES). In addition to these meetings, we also met several times on-site at carpet cleaning businesses to better understand their needs. Finally, we gave a presentation of our design and test results, including

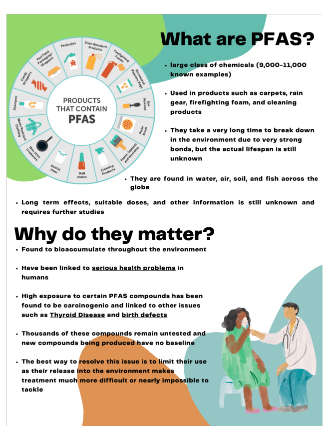
sharing the pamphlet and video resources we created, to 25 staff scientists and engineers (including PE's) at our state's Department of Environmental Services.

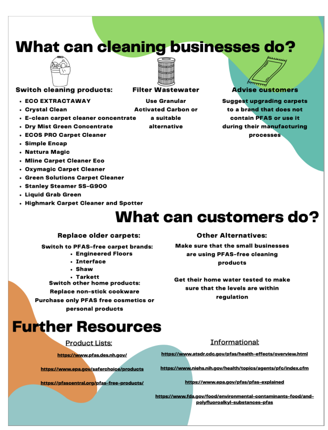
Protection of health, safety, and/or welfare of the public

In addition to technical deliverables, our project's educational deliverables include a public outreach event, an educational pamphlet on PFAS for users and for the general public, and an identified hand-off mechanism for the open-source design materials that we have created.

To spread awareness about our open-source PFAS wastewater filtering system and move toward eventual widespread implementation, our team presented our project to our state's Department of Environmental Services' Environmental Health Program during a staff meeting on March 9th, 2023 11 AM – 12 PM EST. The materials used for the presentation were from the project's capstone final presentation and included a lengthier research background and overview of the system and test results, as this was 35-minute presentation followed by a 25-minute question period. Presentation materials were reviewed and pre-approved by the project's sponsor business lead, Dr. Jennifer Harfmann. The audience was composed ofDES officials and staff members, many of whom are involved in outreach programs or are part of teams involved in chemical pollution reduction initiatives, including several PE's. Approximately 25 employees of the Environmental Health group attended.

Acknowledging that our project has a public impact, we prepared an educational pamphlet for small businesses, customers, and the general citizenry. We recognized the plethora of information available throughout the internet and in various publications. One of the goals for this pamphlet is to distill this information down to the necessary information to educate the public about PFAS. Another goal is to begin to educate the stakeholders about the dangers of PFAS and the importance of filtering these substances to prevent PFAS from entering the environment. The team determined that this would be an effective way to communicate the importance of the filter we designed, since one barrier to adoption of a PFAS filter by small cleaning businesses that we identified is the lack of knowledge regarding what PFAS are. In addition to information about our design, the pamphlet includes alternative cleaning products as described in the EPA Safer Choice product list. The final component of this pamphlet provides further educational links and lists of PFAS free products. This allows for further reading and research if the individual chooses. The pamphlet is a simple way to spread information to the relevant stakeholders. The pamphlet is shown.





Our team has contacted APPLETREE (Agency for Toxic Substance and Disease Registry's (ATSDR's) Partnership to Promote Local Efforts to Reduce Environmental Exposures), which is a DES program aimed at public education. We are pursuing listing and archiving our project materials in APPLETREE's state Environmental Health Guide, which they describe as "a table of resources designed to help legislators, city and town health officers, municipal officials, administrators, and other stakeholders find the appropriate State resource or agency to address environmental concerns raised by your community" (DES and Public Health, 2022A). The guide includes a section about human-made chemicals, which has a PFAS sub-section in which we believe our project fits. However, the process of integrating a new item into a government pamphlet is lengthy and bureaucratic, and thus the integration will happen after the end of our project. Still, to start the process and bring attention to our project is a significant step toward spreading awareness, even if the addition to the APPLETREE site is completed after the project has been handed off to our sponsor.

Multidiscipline and/or allied profession participation

This project succeeded with the help of professional engineers, faculty researchers in the department of epidemiology, and PFAS experts at the state's Department of Environmental Services.

As a group, we lacked a strong chemical background foundation and relied on our advisor, Dr. Megan Romano, and other PFAS experts on campus as consultants for the project. Lab instructor and mechanical engineer Raina White advised us regarding fluid mechanics for our design. The team's sponsor, Dr. Jennifer Harfmann, has extensive practical experience with PFAS removal and thus served as a resource for our group to further investigate the current PFAS removal landscape as well as aid us in contacting stakeholders. Finally our technical advisor, Vicki May, PE, PhD, was instrumental in guiding us through the design process, particularly prototyping quickly so that we had time to get test results and iterate through a second filter prototype design.

Knowledge or skills gained

Our project helped us to improve our knowledge and skills in the following areas:

- Data visualization,
- Scientific research
- Ethical considerations in design and technical communication,
- Prototyping,
- Chemical analysis,
- Statistical analysis,
- Design for usability (plumbing!) and accessibility,
- Fastener design,
- Technical communication, and
- Environmental engineering