

EFFICACY OF MAZAMA PUMICE FOR 6PPD FILTRATION

by

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A THESIS

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Since the 1970s, the chemical 6PPD has been used as a tire preservation agent. Its presence is vital to the function and longevity of tires. When melted tire wear particles are left on roadways, 6PPD acts as a residue and seeps into the environment. 6PPD is a potent environmental pollutant and has been detected in nearly every natural solid, like soils and sediments. Evaluating avenues for 6PPD removal is an important step to a healthier environment and has broader impacts for the removal and mitigation of other pollutants like its toxic derivative, 6PPD-quinone. So far, scientific studies have found only one successful filtration medium for 6PPD-quinone: an engineered soil called high performance bioretention mix (HPBRM). Though this method is effective, it focuses on the filtration of 6PPD-q as opposed to the filtration of 6PPD, more generally. In addition, overuse of HPBRM can lead to harmful algal blooms, so more work is needed to find the most optimal filtration solution.

Other studies successfully filtered graywater and water contaminated with heavy metals using pumice, which is a highly porous volcanic rock formed during explosive eruptions. This medium shows promise due to its success removing other contaminants yet has not been tested with 6PPD. Due to the prevalence of volcanism around the Pacific Northwest, pumice is a cheap, common material that would be relatively easy to implement as a filtration medium.

This study tested the ability of pumice from Mt. Mazama (Crater Lake) to filter 6PPD from a solution using column flow experiments. The main result of this study shows that the pumice size fractions used in this experiment interacted with the 6PPD solution but were not as effective at filtration as the HPBRM. A secondary result shows that surface area and porosity facilitate 6PPD filtration, which should inform future tests on other filtration media for 6PPD and 6PPD-quinone. To successfully implement a filtration medium into the environment and remove 6PPD, more tests must be done to see how these materials perform in a field-based setting.

Acknowledgements

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A Haiku

6PPD is
bad for the environment.
Can small pumice help?

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Background

6PPD, 6PPD-q, and the environment

Since the 1970s, the chemical N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine (commonly known as 6PPD) has been used as a rubber preservation agent. Its presence is vital to the function and longevity of tires and other rubber products (Lane et al. 2024). Friction from the tires' interaction with roadways creates heat, which melts off small rubber pieces. When melted tire wear particles (TWPs) are left on roadways, 6PPD reacts with ozone to become the toxic derivative 6PPD-quinone (6PPD-q) (Figure 1). This 6PPD derivative harms aquatic organisms such as Coho salmon, a cultural and economic cornerstone of the Pacific Northwest. When tires interact with roadways, small particles wear off and are washed into urban streams, where 6PPD-quinone kills Coho salmon in miniscule amounts. This quantity that causes acute mortality in Coho salmon is only 0.041 µg/L, or 0.041 parts per billion (ppb) (Bohara et al. 2024, Lo et al. 2023). 6PPD-q is also associated with a decreased body mass index (an approximate measure of if someone is over- or underweight. A low body mass index indicates a person is underweight) and increased rates of diarrhea and influenza in children (Zhang et al. 2024). Aside from the toxic derivative 6PPD-q, 6PPD by itself is a potent environmental pollutant and has been detected in nearly every natural solid (Iqbal et al. 2025, Lane et al. 2024, Yi et al. 2025). Evaluating avenues for 6PPD removal is an important step to a healthier environment and has broader impacts for the removal and mitigation of other pollutants like 6PPD-q.

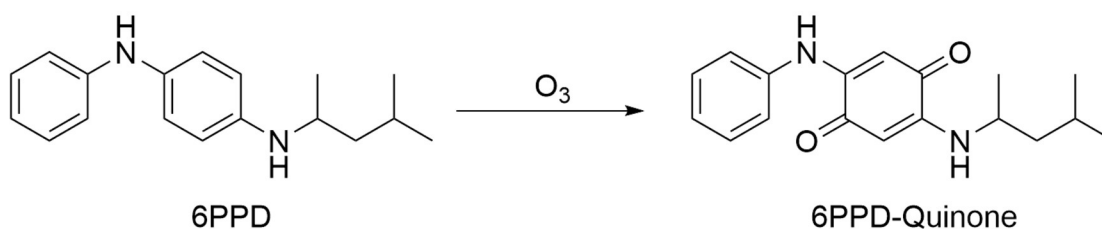


Figure 1. The chemical structures of 6PPD and 6PPD-quinone.

Taken from Fujifilm, n.d.

6PPD-q removal efforts

There have been a few attempts to remove 6PPD-q from aqueous environments. An experiment found that permeable (porous) pavements served as an effective filter that trapped TWP and decreased 6PPD-q levels to below the lethal limit for Coho salmon (Mitchell et al. 2023). This creates an obvious solution for the 6PPD-q contamination problem: re-pave every road in the Puget Sound watershed with a more porous cement variety. Unfortunately, that is not economically feasible. One can imagine that the cost of re-paving every street in Seattle alone with a new cement variety would simply be impossible.

Another avenue for 6PPD-q removal was discovered in March 2025. This used an engineered soil known as high performance bioretention mix (HPBRM), made of 70 vol% sand, 20 vol% coconut coir (husk), and 10 vol% biochar (high carbon wood ash) by volume. The HPBRM prevented Coho mortality in 100% of tests when it was used to filter stormwater (Mitchell 2025). Though this is a promising breakthrough, HPBRM is not a perfect filter; it may exacerbate water quality issues in some cases. One main issue with HPBRM is the possibility for phosphorus leaching, which can lead to algal blooms and other issues within an ecosystem (Howie & Lubliner 2024). Because of this fact, HPBRM is best used in moderation, and other avenues for 6PPD-q filtration are worth investigating as a supplement to this new discovery.

In addition, though these two methods are effective and important for pollutant removal,

they focus on the filtration of 6PPD-q. Avenues for 6PPD removal have been less widely studied.

Pumice and its capabilities as a filter

Pumice is a product formed during explosive eruptions that occurs when magma containing dissolved volatiles (mostly water) ascends toward the surface, sees its volatiles exsolve in the formation of gas bubbles, and erupts from a volcano. Researchers have extensively investigated pumice's capability as a filtration medium. In a recent study, pumice was successful at removing nutrients from and decreasing the turbidity of graywater (Price et al. 2025). In addition, it can decrease the concentration of heavy metals in graywater with the assistance of plants (Chowdhury et al. 2018). Pumice's efficacy for graywater filtration is due to its high surface area within a given volume and its high porosity (Price et al. 2025). Because filtered graywater can be used for gardening, laundry, or dishwashing, this discovery made pumice graywater filtration a widely applicable method that has gained a lot of attention among sustainable designers and engineers. In fact, as this method is becoming more widespread, there are companies, such as the startup, Waterleaf, that have begun to specialize in domestic graywater filtration (Dorsch, 2026).

Because of pumice's ability to remove contaminants from wastewater and the fact that 6PPD-q is removed from stormwater by porous pavement, it stands to reason that pumice would be an effective filter for 6PPD and 6PPD-q. In addition, due to the prevalence of volcanism around the Pacific Northwest, pumice is a cheap, common material that would be easy to implement as a storm drain filter throughout the region. If successful, pumice filtration could help ensure that wastewater reaching natural waterways would be less abundant in 6PPD and 6PPD-q, and by extension Coho mortality rates would decrease.

Research Question and Objectives

Given this pertinent environmental and human health issue, and the possible mitigation solution using pumice, this thesis seeks to answer three main questions:

1. Can HPBRM filter 6PPD in addition to 6PPD-quinone?
2. Can pumice remove 6PPD from a solution as effectively as HPBRM?
3. What characteristics of HPBRM and/or pumice facilitate 6PPD filtration?

Methods

To answer each question within this study, I completed two different objectives: particle analysis and filtration experiments. For the particle analysis, I analyzed various important parameters of each sample to evaluate why HPBRM is an effective filter and to test whether pumice has similar qualities. For my main filtration experiments, I used column experiments to pump the solution through the filtration media (Figures 5, 6) and compared the concentration of influent and effluent.

Materials

I used four size fractions of pumice from the 7.7 ka climactic eruption of Mt. Mazama: 0.5-1 mm, 1-2 mm, 2-4 mm, and 4-8 mm. In addition, I created a fifth sample by mixing these four grain sizes, combining equal parts of each size fraction by volume. The pumice was obtained from South Chemult Quarry in January 2024. In addition to the pumice size fractions, I ran experiments with HPBRM, which I obtained from Walrath Soil Technologies in May 2025, and dense glass beads to compare their properties to those of the pumice. Figures 8 and 9 show microscope photos of every material in detail.

In addition to my filtration media, I obtained solid 6PPD from MedChem Express in December 2025. I also used potassium hydrogen phthalate (KHP) to test a spectrophotometric chemical detection method, which I obtained in November 2025 from MedChem Express. Finally, my solute was distilled water which was distributed in plastic gallon jugs.

Particle Analysis

The main filter-medium properties of interest to my study were mass, volume, density, surface area, diameter, porosity and packing fraction (Figure 2). These measurements were made

on the pumice and HPBRM media. However, because glass beads are spheres of with constant parameters and zero porosity (and thus permeability), I did not take in-depth measurements on them and only measured their packing fraction as part of this study.

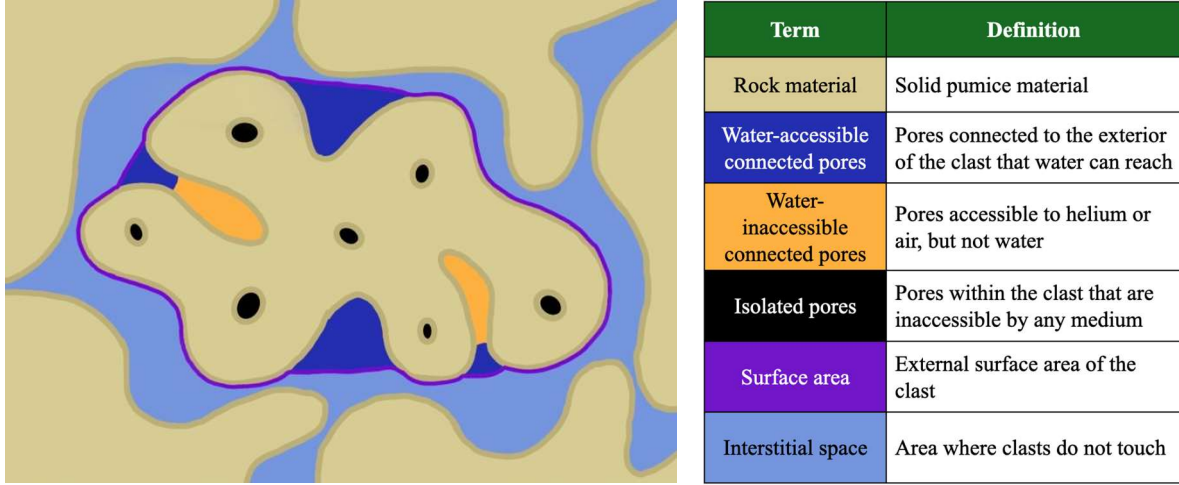


Figure 2. A diagram of some of the parameters of pumice described in the methods.

Modified from Price et al. 2025.

Mass, Volume, and Density

Mass, volume, and density measurements are important because they help differentiate the diverse characteristics of different size fractions. To find the mass (m), I weighed each sample on a mass scale, correcting for the weight of the container. I used the dimensions of the inside of the columns used for the main filtration experiments to find the bulk volume of pumice (V_b), which was a constant 350 cm^3 across every sample. From these mass and volume values, I was able to calculate the bulk density of each sample (ρ_b) using Equation 1:

$$\rho_b = \frac{m}{V_b} \quad (1)$$

Equation 1. The relationship between density, mass, and volume.

This bulk density value represents the density of the entire clast, including the void spaces filled by air within the individual clasts (i.e., the porosity).

In addition to the mass, bulk volume, and bulk density of dry pumice, I also investigated the mass and volume of water held in pore space by the pumice. To find the mass (m_{water}), I soaked each sample in water for 1-2 minutes, then drained the excess water and took the mass using the same method as the dry pumice. I subtracted the dry mass value (m_d) from the wet mass value (m_w) of each sample (Equation 2), which yielded a result indicative of the mass of excess water in the pore space within the pumice. By using the relationship between mass, volume (V_{water}), and the density of water (ρ_{water} , 1000 g/cm³) (Equation 3), I was able to convert the mass of the stored water within the pumice to a volume.

$$m_{\text{water}} = m_w - m_d \quad (2)$$

Equation 2. Mass of water stored in pores of pumice.

$$V_{\text{water}} = \frac{m_{\text{water}}}{\rho_{\text{water}}} \quad (3)$$

Equation 3. Volume of water stored in pumice from its mass and density.

I then added this value to the quantity of interstitial space within the column (V_{int}) (Equation 4) to get the total amount of water stored in the column (V_{tot}) (Equation 5).

$$V_{\text{int}} = V_b - V_e \quad (4)$$

Equation 4. Volume of interstitial space within the column.

$$V_{\text{tot}} = V_{\text{water}} + V_{\text{int}} \quad (5)$$

Equation 5. Total volume of water-accessible space within the column.

Surface Area and External Volume

Because the external surface area is an established control on the filtration efficacy of pumice (Price et al. 2025), it was important to quantify each size fraction's surface area for these experiments. To do this, I used the MicroTrac PartAn3D Particle Analyzer (PartAn) to image and quantify the external volume and surface area of each clast (Figure 2). The PartAn drops

individual particles in front of a high-speed, high-resolution camera, taking many images of each particle as it falls (Figure 3). These images are used to calculate a surface area and external volume (V_e) for each particle, which can be summed to calculate the total volume and surface area of grains that make up a sample filling a 350 cm³ container.

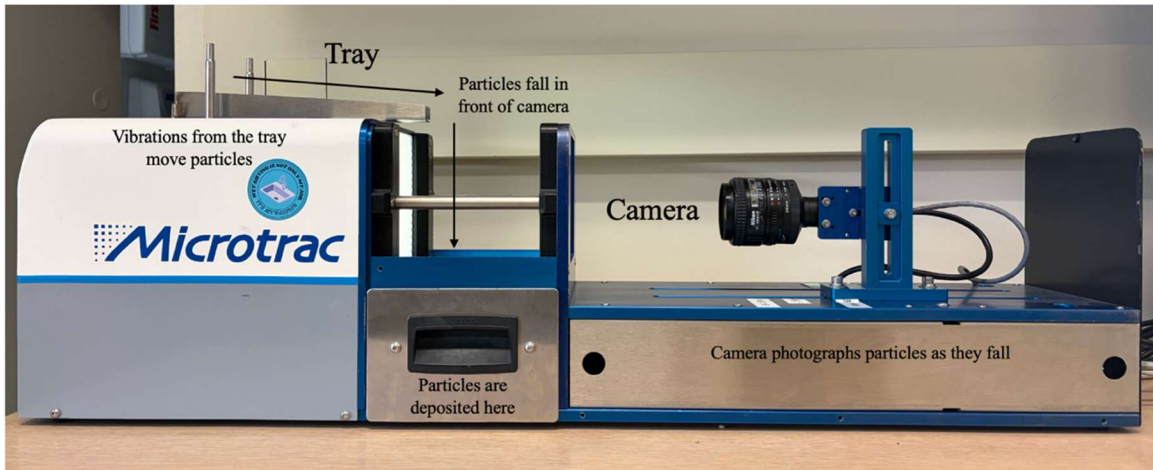


Figure 3. Photograph of MicroTrac PartAn^{3D}.

Pumice clasts are placed on the vibrating metal tray (upper left) and fall in front of the camera, which images the clasts on their descent. This process records physical measurements about clast dimensions, volume, surface area, and shape. Modified from Price et al. 2025.

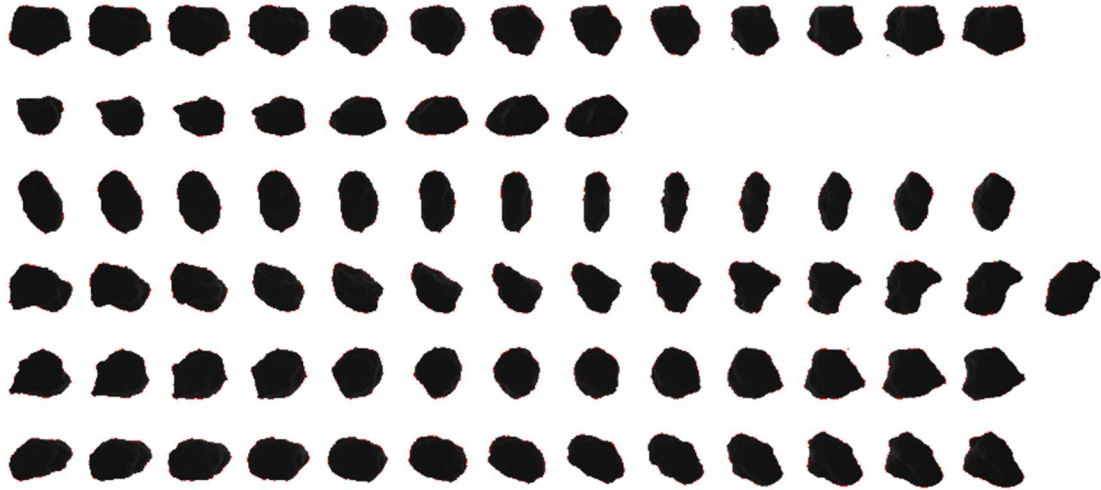


Figure 4. Photographs of particles from the PartAn

Each row shows all the individual scans of a single particle as it falls in front of a high-speed, high-resolution camera.

Porosity and Packing Fraction

Using data from the PartAn and pycnometer, I calculated the porosity and packing fraction of each sample.

Porosity

To find the density of the rock material itself, without any additional trapped gas, I used the Accupyc Helium Pycnometer (pycnometer). The pycnometer works by evacuating a small chamber full of air by pumping in helium, which is a small enough molecule to penetrate fully into each pumice vesicle, provided it is connected to the exterior of the clast. The volume returned by the instrument is the volume of solid (including glass and crystals, if present), plus any bubbles inaccessible to helium (i.e. isolated bubbles).

The porosity of a clast (ϕ) is a ratio that is equal to the volume of void space within a sample divided by the total volume of the clasts and thus varies from 0-1. Pumice has a high porosity, usually falling within a range of 0.5-0.9. The total porosity (ϕ_t) is a specific ratio between the density of the bulk sample (ρ_b) and the density of the crushed sample (ρ_c) (Equation

5). The bulk sample is less dense than the crushed sample because it includes any pores within the particle, while the crushed sample is the density of only the solid rock material. We can find the density of both using Equation 4:

$$\rho_b = \frac{m_d}{V_e}; \rho_c = \frac{m_c}{V_c} \quad (4)$$

Equation 4. Finding the density of the bulk sample and the crushed sample using the relationship between mass, volume, and density.

$$\phi_t = 1 - \frac{\rho_b}{\rho_c} \quad (5)$$

Equation 5. Total porosity.

The bulk density uses the dry mass and the external volume from the PartAn, while the density of the crushed particles uses the mass of the crushed particles (m_c ; which is assumed to be identical to m_d because the only difference between the two samples is the absence of air, which is a negligible portion of the mass) and a volume value for the crushed particles given by the Pycnometer (V_c).

Connected porosity (ϕ_c) refers to the proportion of the clast occupied by void space that is accessible to water or helium (i.e. the accessible void space in Figure 1). This value is a ratio between the bulk density and the density of rock material plus any isolated pores (ρ_h , Equation 7). ρ_h is calculated similarly to the parameters in Equation 4, using the volume of hard rock material plus isolated pores given by the pycnometer (V_h , Equation 6).

$$\rho_h = \frac{m_d}{V_h} \quad (6)$$

Equation 6. The density of the hard rock material plus any isolated pores.

$$\phi_c = 1 - \frac{\rho_b}{\rho_h} \quad (7)$$

Equation 7. Connected porosity.

Isolated porosity (ϕ_i) refers to the proportion of a clast that is occupied by bubbles that are completely isolated from the outside of the clast by solid material. To find the isolated porosity, we can subtract the connected porosity from the total porosity (Equation 8):

$$\phi_i = \phi_t - \phi_c \quad (8)$$

Equation 8. Isolated porosity.

Packing Fraction

The packing fraction (PF) of a sample is a measure of how closely individual particles stack together. This is a ratio of the bulk volume, including the volume of interstitial space (350 cm³, V_b) and total external volume of each clast (obtained by the PartAn) within a sample (Equation 9):

$$PF = \frac{V_e}{V_b} \quad (9)$$

Equation 9. Packing fraction.

Packing fraction differs from one size fraction to another, and is a necessary comparison between pumice, HPBRM, and beads to see if it has a correlation with filtration efficacy.

6PPD Dissolution & Detection

To make my experimental solution, I dissolved solid 6PPD with 95% purity in distilled water. To facilitate dissolution, I added 25 mL of HCl per liter of solution. I used an influent concentration of approximately 62 mg/L of 6PPD for all of my filtration experiments. The solution was chilled in glassware at 10°C when not in use, according to best practices from Lane et al. (2024).

I used an ultraviolet-visible light (UV-VIS) spectrophotometer to take the spectra of each influent and effluent sample in triplicate. Because 6PPD has a high carbon content, it presents a high absorbance signature at approximately 280 nm. Differences in the amplitude of this peak reflect differences in concentration, so I compared the integrated area under the peaks of the effluent spectra to the peak of the influent spectra. This allowed me to quantify a percent change in the area under each peak, which is what I reported as the percent change in the concentration of the 6PPD solution. To ensure the accuracy of this new method, I compared the 6PPD calibration curve to a preliminary calibration curve using KHP following the methods of Kim et al. (2016).

In addition to the spectrophotometric analysis, I also measured the pH of the influent and effluent samples using the OrionStar A121 Portable pH Meter. This step helped me quantify how the addition of HCl affected the pH of the 6PPD solution and evaluate if 6PPD itself influenced the solution's acidity.

Preliminary Bottle Experiments

To quantify the sorption abilities of pumice and HPBRM, and to evaluate 6PPD's behavior over time, I measured the concentration of 6PPD as different media interacted with the solution over 48 hours. To do this, I put 750 mL of 50 mg/L 6PPD solution in glass bottles (Figure 4) with 400 cm³ of pumice, HPBRM, or 4-8 mm-diameter glass beads. I then let these bottles sit and took 30 mL samples of the solution at 30 minutes, 1 hour, 2 hours, 5 hours, 12 hours, 24 hours, and 48 hours. Finally, I used the UV-VIS detection technique to find the concentration of 6PPD in the solution for each sample.



Figure 5. Bottle experiment set-up.

Column Experiments

I constructed individual columns with a 50- μm -diameter filter paper and glass wool barrier on the influent side and a 50 μm filter paper barrier on the effluent side (Figure 6). Each column held 350 cm^3 of sample between those layers. This setup is commonly used in column experiments. The effect of the filter paper and glass wool on the filtration of the solution was negligible (Price et al. 2025), and their presence was necessary to prevent the sample from clogging or puncturing the tubes. The glass wool on the bottom also promoted diverse flow paths within the columns; without it, the solution would have been more likely to simply take the path of least resistance on the sides of the column.

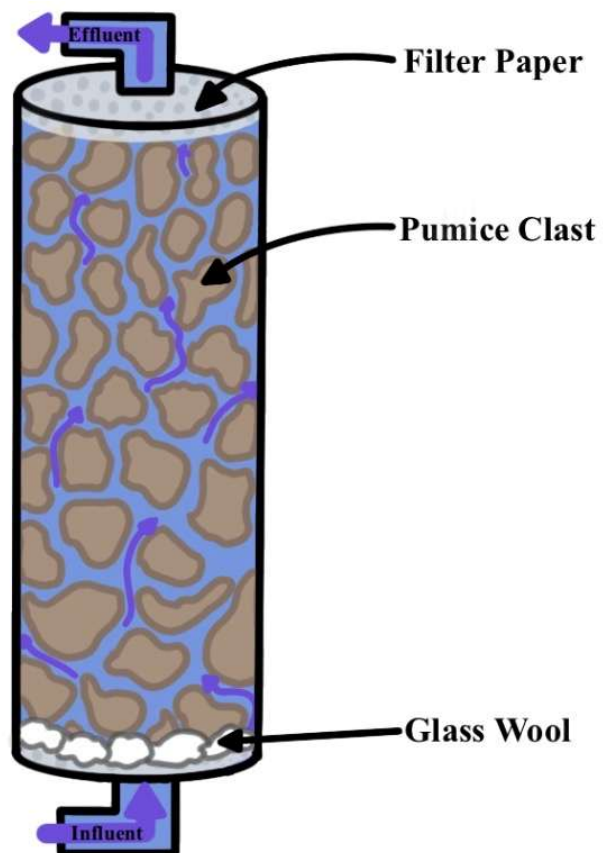


Figure 6. Individual column set-up for the main experiments.

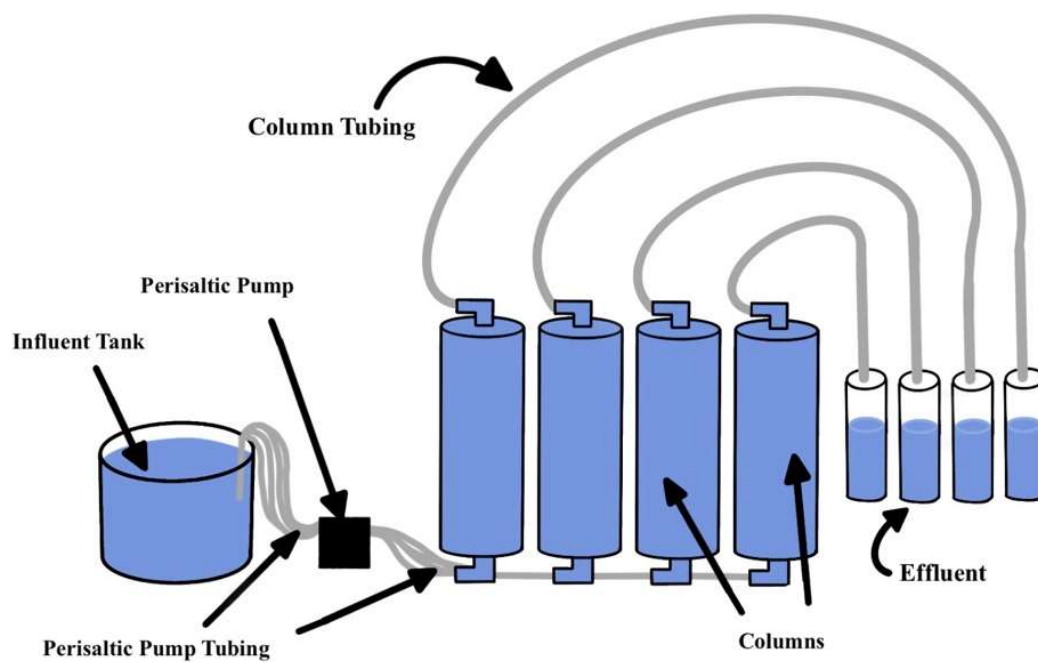


Figure 7. Full column set-up for the main experiments.

Before I pumped the 6PPD solution through the columns, I did a preliminary run with columns full of pumice or soil and pumped distilled water through. I then used the UV-VIS to take the spectra of that effluent, which helped me minimize any interference that the pumice or soil might have presented in the spectral analysis.

I pumped my 6PPD solution through the columns using a peristaltic pump at a constant rotation rate of 80 RPM. This correlates to a flow rate between 9 and 11 L/hr. Flow rate increases as size fraction increases because the increased amount of interstitial space provides a less tortuous path for water to flow through (Price et al. 2025). Approximately 30 mL of effluent was collected from each sample (Figure 6), after which I disconnected the column from the pump. Thus, each column was only run through once and 6PPD solution was not cycled through the sample. After the effluent was collected, I used the UV-VIS to determine its concentration.

All samples (i.e. the HPBRM, the glass beads, and the different pumices) were analyzed in triplicate, meaning that I used three columns of each size fraction and took the average as my main result, for a total of 21 columns. Because my column set-up facilitated batches of ten columns, I ran the whole process three times and used different batches of influent solution for each. This was necessary because creating one batch of solution for everything would have required a massive container, the likes of which we did not have in the lab.

Data Analysis

After completing the spectrophotometric analysis for each sample, I used OriginLab to analyze the spectral data (Appendix B). The amplitude under the peak caused by 6PPD correlates to the concentration of 6PPD present in the solution, so I was able to evaluate changes in concentration by a change in area under the peak. After normalizing my spectra from 0-1, I began data analysis. Because of the peak in the absorbance spectra of 6PPD at approximately

280 nm, I used a diagnostic integration window of 263-290 nm to integrate the area between a baseline spectrum of distilled water and each spectra curve (A_p). Then, to account for interference signals from pumice or soil, I subtracted the integrated area between the baseline and spectra from a distilled water blank which had run through the relevant media (A_m) (Equation 9).

$$A_e = A_p - A_m \quad (10)$$

Equation 10. The area of the effluent curve, normalized to remove interference signals from the filtration medium.

After I found the area under each curve, I subtracted the area of the effluent (A_e) from the area of the influent (A_i) to find the change in area between the two (ΔA) (Equation 10).

$$\Delta A = A_e - A_i \quad (11)$$

Equation 11. Change in area between the influent curve and the effluent curve.

Then I converted that into a percentage (Equation 11), which controlled for any discrepancies in influent concentration between column runs.

$$\text{percent removed} = \frac{\Delta A}{A_i} \times 100 \quad (12)$$

Equation 12. Calculation of the percentage of 6PPD removed from the solution.

Results

Filtration media characteristics and size distribution

Pumice

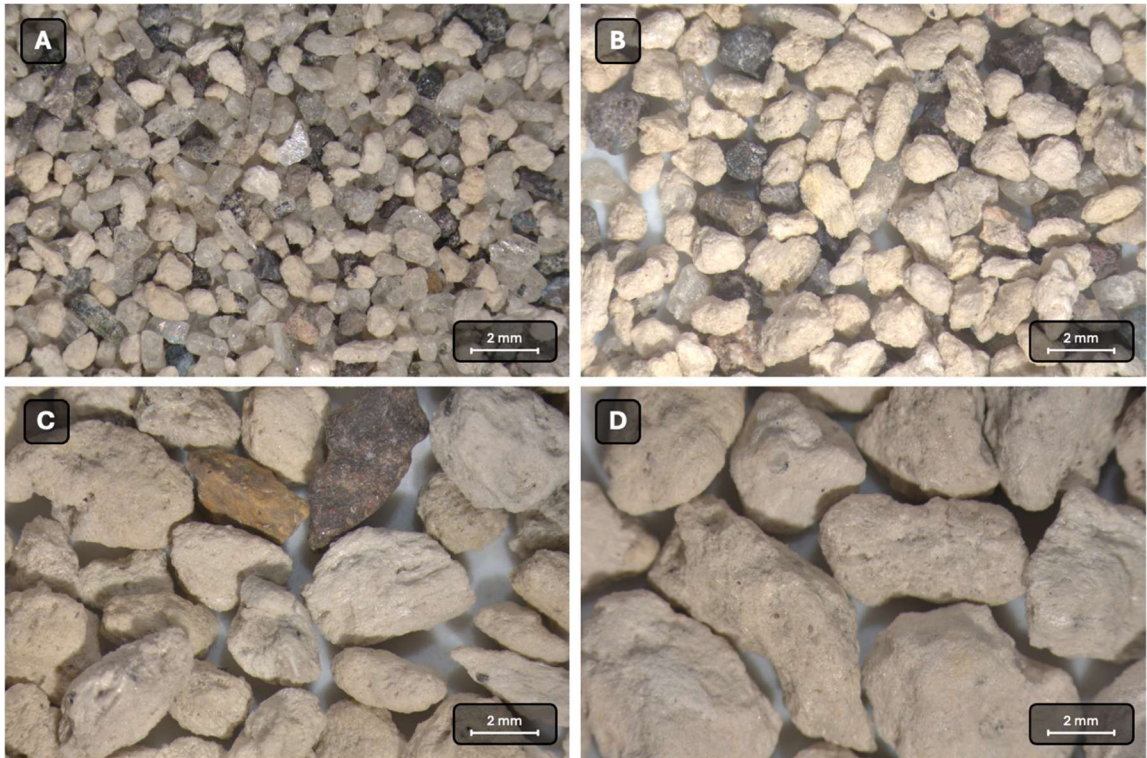


Figure 8. Microscope pictures of different pumice sizes taken at the same magnification.

0.5-1 mm (A), 1-2 mm (B), 2-4mm (C), and 4-8 mm (D).



Figure 9. Microscope photos of HPBRM, glass beads, and pumice.

Microscope photos comparing HPBRM (left), glass beads (middle), and mixed size fraction pumice (right).

Figure 8 shows pictures of each constant size fraction of pumice, taken under a microscope. Qualitatively, it is evident that the presence of lithic (hard rock) fragments decreases as size fraction increases. Lithics are smooth, sometimes glassy, and not porous, which means they have less internal surface area than a pumice particle. This contributes to the low porosity of the small size fractions, shown in Figure 10. Figure 9 shows the mixed size pumice, the HPBRM, and the glass beads. The mixed size pumice has a lower proportion of lithic fragments than the smaller constant size fractions, but more lithics than the 4-8mm size fraction. Because it is a mix of all the constant size fractions, its physical properties often fall somewhere in the middle of all the pumice samples (Figure 10, 17).

The two main qualitative parameters of interest are external surface area and porosity. The 4-8mm size fraction has a low external surface area (Figure 17) yet a high porosity (Figure 10), which alludes to a larger surface area inside the clast that is not accounted for in the *external* surface area measurement. The mixed size fraction has the highest porosity out of any pumice sample and a relatively high external surface area (Figure 10, 17), which means it likely has the most surface area per unit volume.

HPBRM

The microscope photo of the HPBRM (Figure 9) shows a large size difference between the sandy matrix and the biochar pieces. This supports the high packing fraction shown in the data (Figure 17), as the small sand particles can fill interstitial space between the biochar. Figure 10 shows that HPBRM has the lowest porosity, yet all the pores are interconnected. This high connectivity enables the most contact between the porous particles and solution out of any medium tested.

Connectivity vs. Total Porosity with Size Fraction

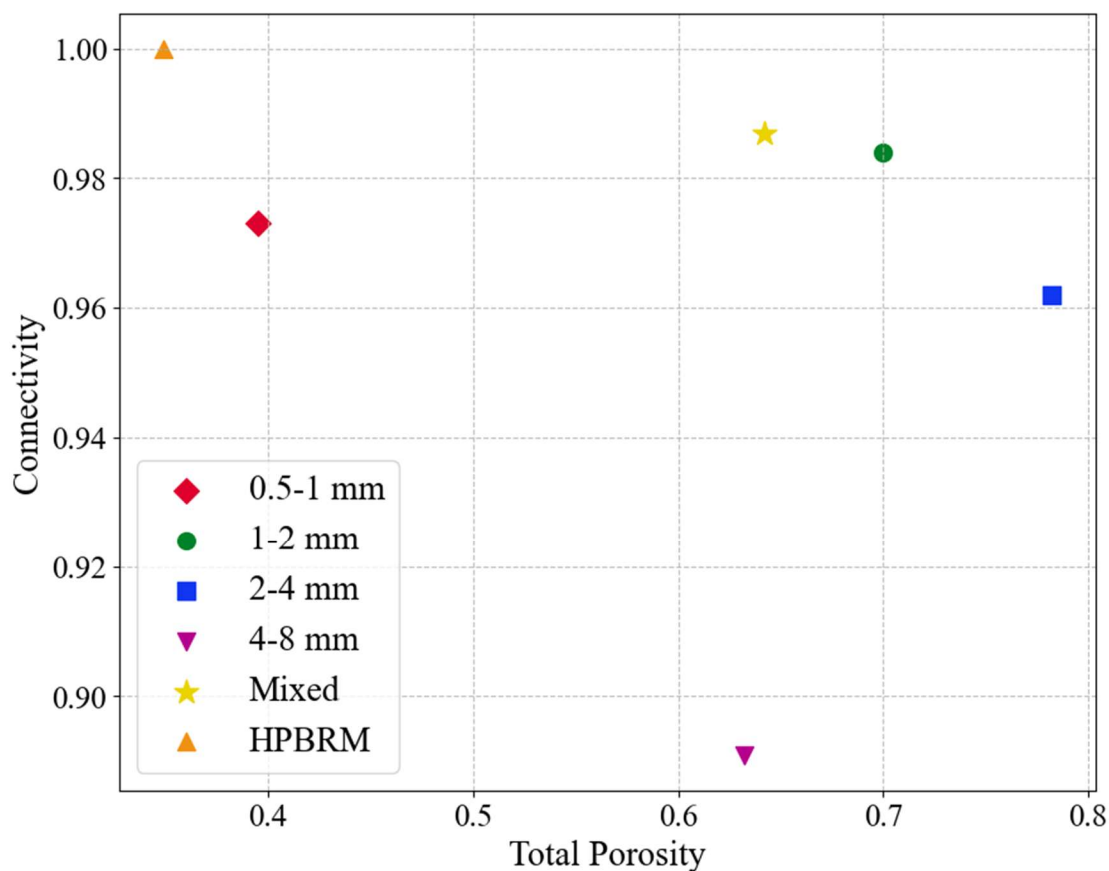


Figure 10. Total porosity and connected porosity.

A graph showing the total porosity of each sample on the x-axis, and the connected porosity of each sample on the y-axis. The legend shows markers for each size fraction.

6PPD solution's behavior over time in static test

When left out at room temperature, 6PPD concentration was relatively constant between zero and twelve hours, degrading to 89% of the original concentration at hour 12 (Figure 11). After hour 12, there was a spike in concentration which put the solution at approximately 120% of the original concentration. Because of the incomplete dissolution of 6PPD in this solution, this high percentage implies that when left alone at room temperature, previously exsolved 6PPD will dissolve in the solution.

6PPD Behavior Over Time

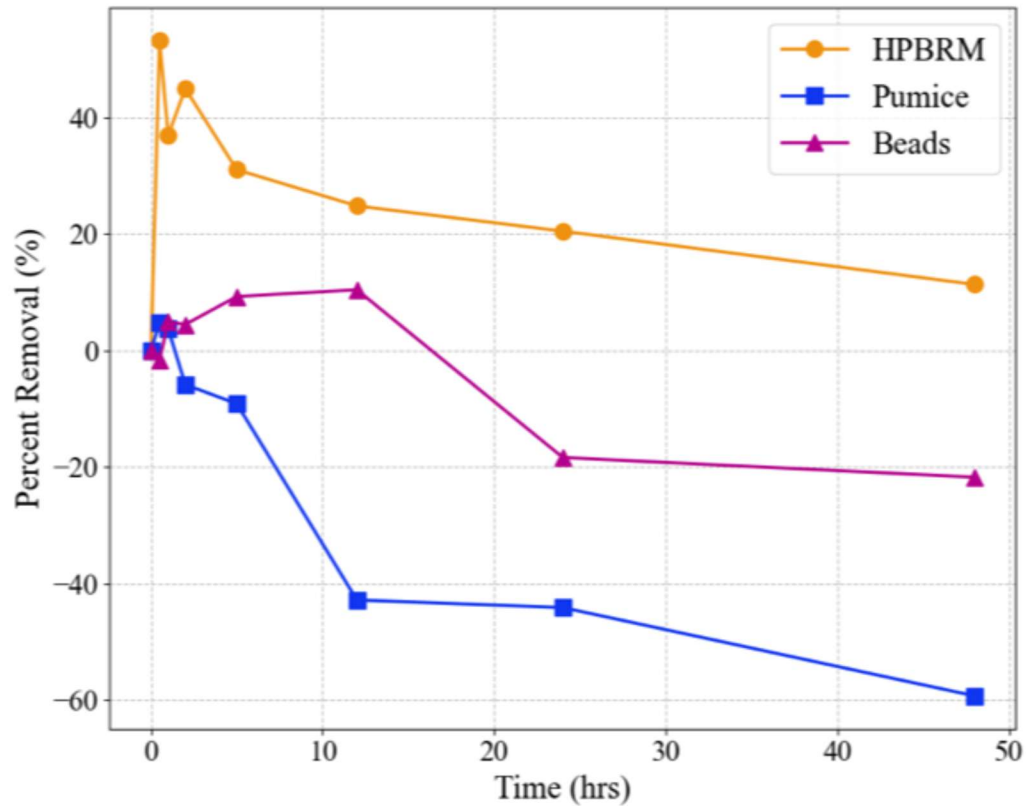


Figure 11. Bottle experiment results.

A graph showing the percent of the original concentration removed over time. A positive percentage implies removal while a negative percentage implies dissolution of previously exsolved 6PPD.

Sorption ability of pumice and HPBRM in static test

Pumice

Between the beginning of the experiment and the one-hour mark, pumice absorbed a small amount of 6PPD. However, after two hours, the concentration of 6PPD had gone back to zero. Between five and twelve hours, there was a sharp increase in 6PPD concentration to approximately 142% of the starting concentration. This continued to increase through the end of the experiment, which shows the 6PPD concentration at 159% of the starting concentration (Figure 11). Similar to the control, this high percentage at the end of the experiment implies

further dissolution of 6PPD. Because the percentage of 6PPD in the solution at the end of the experiment is almost 40% greater than that of the control, I believe there is a chemical characteristic of the pumice that facilitates 6PPD dissolution in still-water settings.

HPBRM

After 30 minutes, HPBRM had already absorbed to its full capability, which was around 53% of the starting solution's concentration. After two hours, the amount of 6PPD removed by the soil stopped fluctuating and started slowly decreasing, indicating that the soil was releasing 6PPD back into the solution (Figure 11). This trend continued until the end of the experiment, where the soil absorbed less than 20% of the 6PPD present in the starting solution.

Column results

Each filtration medium reacted with the 6PPD differently (Figure 13). The glass beads had little to no effect, while the pumice and HPBRM successfully filtered varying percentages of 6PPD. The HPBRM was the most successful media out of all tested, filtering an average of 82% of 6PPD from the influent. The mixed size fraction, on average, was the most effective pumice size tested. In addition, both soil and pumice caused qualitative changes to the color of the solution (Figure 14). This is best illustrated by images from the still-water experiments, but effluent from the columns exhibited a similar phenomenon. The other main qualitative observation from the column study was that the 4-8 mm pumice turned green after contact with 6PPD, which can be observed by both the microscope and the naked eye (Figure 15).

Percent Removal of 6PPD by Different Filtration Media

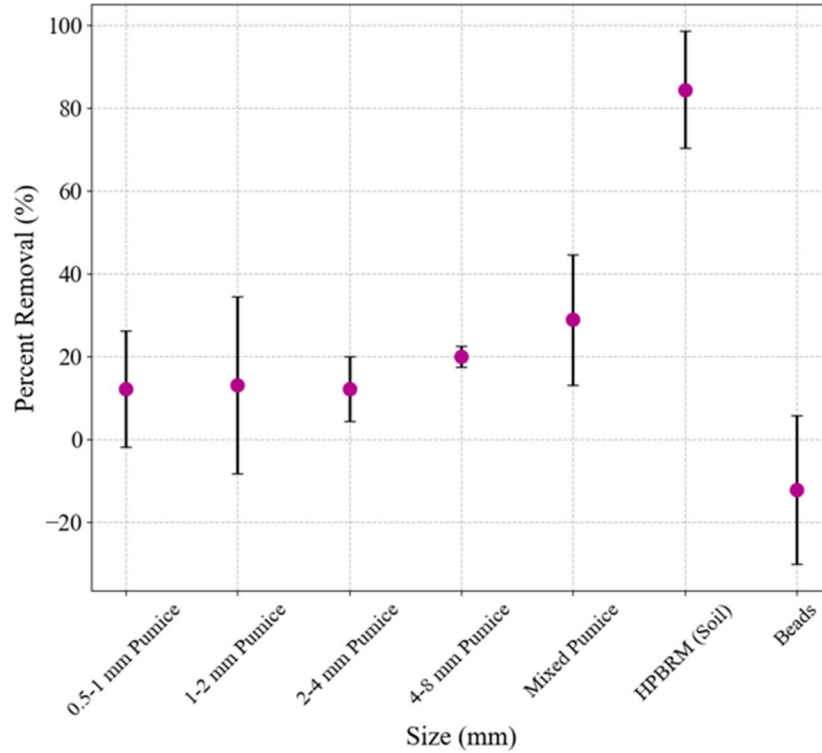


Figure 12. Percent removal graph

A graph showing the percent removal of 6PPD by different filtration media, with error bars. A positive percentage implies a decrease in concentration, while a negative percentage implies an increase in concentration.



Figure 13. Images of the bottle experiments.

6PPD solution at the beginning of the experiment (left, with each filtration media indicated by a vial showing the media and the 48hr time marker), samples taken from the still-water test with soil at each measured time (middle), and samples taken from the pumice still-water test at each measured time (right).



Figure 14. Macroscopic and microscopic images of the 4-8 mm pumice.

Macroscopic image (left) of the before (top) and after (bottom) column experiments (left), and microscopic images of the same pumice (right).

Filtration Media's Effects on 6PPD Removal

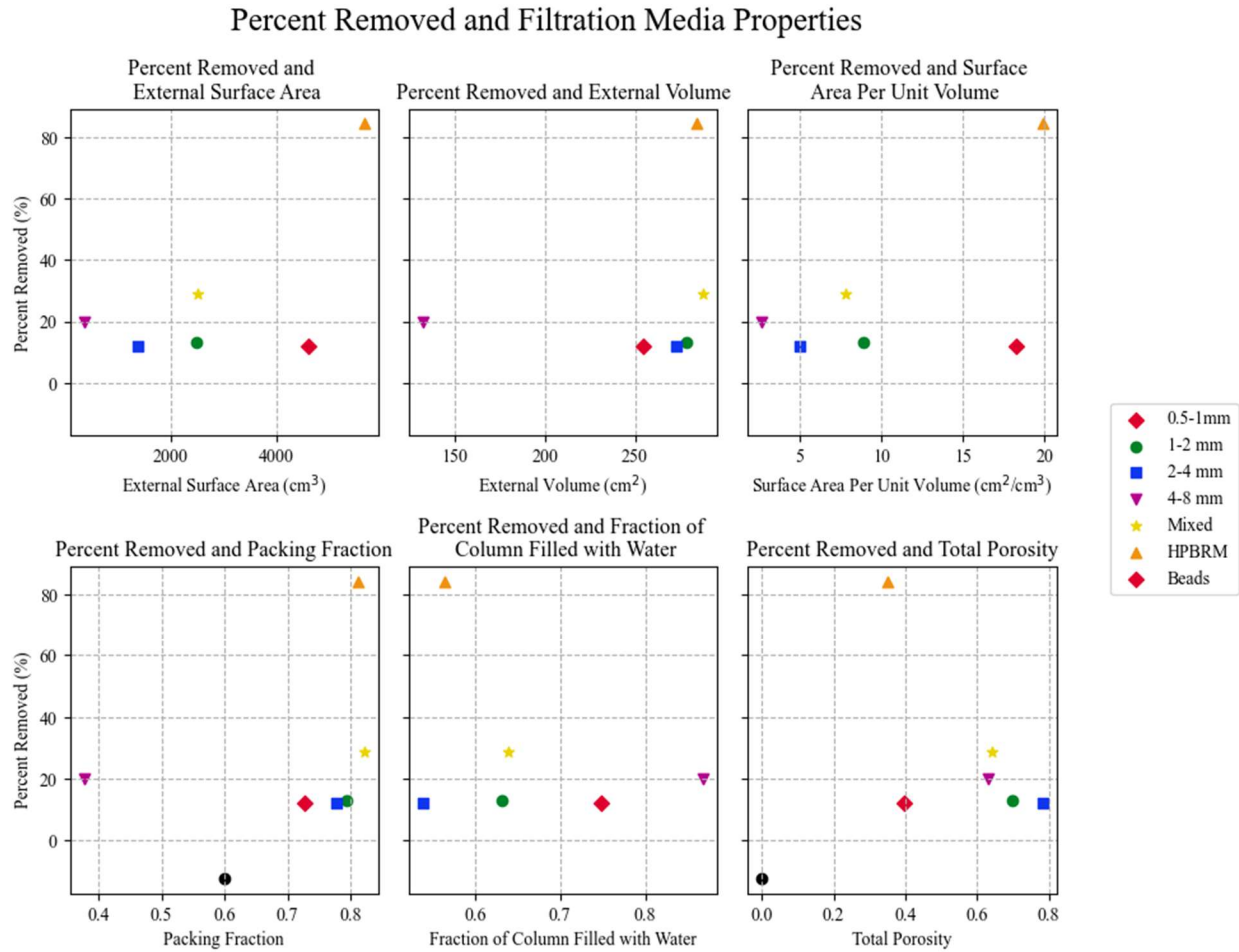


Figure 15. Various important parameters for pumice, soil, and beads' size characterization, correlated with percent removed on the y-axis.

Within the constant pumice size fractions, the 4-8 mm pumice was most effective at removing 6PPD, but its physical properties are usually an extreme opposite from HPBRM, the most effective filter. Alternatively, the mixed size fraction was more effective than any of the constant size pumice and many of its physical parameters fall in the middle of all the constant size fractions. In addition, it has a high packing fraction because the smaller particles can fill space between the larger particles that otherwise would be empty, similar to the soil.

HPBRM

The HPBRM has similar physical properties to the mixed size fraction yet is 40% more effective at filtering 6PPD (Figure 14, 17). This is likely due to differences in the chemical composition of the pumice and the HPBRM. Soil is an effective filter in part due to the presence of organic matter and the presence of certain cations like Ca^{2+} , Mg^{2+} , K^{+} , and Na^{+} (Ihenetu et al. 2025, Spahr et al. 2022).

pH

In addition to the change in the concentration of the solution over time, the pH of the solution also varied slightly. The pH of each sample was between 0.95 and 1.5, depending on the pH level of the influent (Appendix A). The exception was the effluent from the HPBRM in the column runs, which on average increased the pH of the effluent, bringing it closer to neutral. No other medium had this effect in any experiment. In addition, this acidification was entirely due to the addition of HCl, as 6PPD solution without HCl had a pH similar to the distilled water control (Appendix A).

Discussion

What characteristics of HPBRM and/or pumice facilitate 6PPD filtration?

The most important physical parameter of pumice and HPBRM for effective filtration is surface area. This finding is consistent with previous studies that have evaluated pumice's ability to filter other contaminants (Price et al. 2025, Chowdhury et al. 2018). However, an increase in filtration efficacy is not directly correlated with an increase in external surface area. Though the smallest size fraction of pumice has an external surface area similar to the soil, it also has a high fraction of lithic fragments which are not porous. The data shows that as size fraction increases, and thus, as lithic proportion decreases, filtration efficacy increases. In contrast, the 4-8 mm size fraction had the smallest surface area by far and was the most effective of the constant size fractions. This discrepancy is because the 4-8mm size fraction makes up for its small external surface area with its high porosity, which alludes to a large surface area inside the clast. This large internal surface area makes up for the size fraction's low external surface area, supporting the conclusion that an effective filtration medium for 6PPD must have a significant percentage of porous particles and a high surface area.

Packing fraction is another key variable that contributes to filtration efficacy: the 4-8 mm size fraction has a low packing fraction, which means a larger proportion of the column was filled with water during filtration than any other size of pumice. This high proportion of water enabled less interaction between the pumice and solution, potentially hindering its filtration ability. A low packing fraction correlates with a low volume of filtration medium inside the column, which contributes to the low external surface area of the size fraction as seen with the 4-8 mm pumice. Therefore, the high surface area within, between, and on the surface of porous

particles (as exhibited by a high surface area, porosity, and packing fraction) contributes to the filtration efficacy of the filtration medium.

All these factors conclude that an effective filtration medium for 6PPD broadly has a high surface area, either on the exterior of the clasts or inside the clasts. The ideal medium has a high packing fraction, enabling constant contact between the solution and the filtration medium. Finally, an ideal filter for 6PPD must also have a significant percentage of permeable particles, as the high proportion of smooth, impermeable lithic particles in the smaller size fractions hinder filtration efficacy.

In addition, there are chemical factors that make HPBRM the most effective filter, as it has a vastly different chemical composition from Mazama pumice. The presence of key cations and organic matter in the soil contribute to its filtration efficacy. Organic matter in soils consists of complex organic molecules that bind with contaminants through adsorption (Keesstra et al. 2012), which helps sequester contaminants in the soil and remove them from a solution. The cations Ca^{2+} , Mg^{2+} , K^{+} , and Na^{+} have a similar function: they facilitate cation exchange between the solution and the soil. The positive cations bind to negatively charged ions in the solution and thus remove them. Magma from the climactic eruption of Mt. Mazama is primarily rhyodacite (Bacon & Druitt 1988) which means it contains low quantities of many of these important cations, meaning there is less opportunity for cation exchange between a contaminant and pumice than HPBRM.

The fact that soil is so effective shows that the physical properties of a filtration medium like surface area, porosity, and packing fraction are an important constraint on filtration efficacy, but the favorable chemical composition of the soil makes its filtration ability much more effective than what pumice could produce.

Can HPBRM filter 6PPD in addition to 6PPD-quinone?

HPBRM was an effective filter of 6PPD in addition to its proven efficacy with 6PPD-quinone. In fact, it filtered the highest percentage of 6PPD of any medium tested. Questions remain about what characteristic of the HPBRM specifically is most conducive to 6PPD removal. I hypothesize that the addition of biochar to the soil is the main key to success, as other literature has proven biochar to be an effective filter for 6PPD, 6PPD-q, and other organic contaminants (Ihenetu et al. 2025, Spahr et al. 2022). This also supports the interpretation that porosity is an important control on filtration, as biochar is extremely porous.

Can pumice remove 6PPD from a solution as effectively as HPBRM?

Pumice does not remove 6PPD from a solution as effectively as HPBRM. However, there is a difference between the effects of the pumice and the effects of the glass beads on the effluent solution, which suggests that pumice does interact with 6PPD, and effectively removed some of it from the solution. The 4-8 mm size fraction was the most effective of all the constant size fractions and the mixed size fraction was more effective than any of the constant size pumice, removing the most 6PPD from the solution of all the pumice samples. More analysis is needed to determine whether pumice would be an effective mitigation strategy for this pollution issue.

Limitations

pH

To facilitate 6PPD dissolution, it was necessary to add acid to the solution. This decreased the pH to approximately 1 (Appendix A). The low pH of the solution did not have a visible effect on the pumice clasts, and the green color of the post-experiment pumice is a result of the 6PPD solution (shown in the comparison between pre-and post-experiment pumice, Figure 16). However, the pH difference of the pumice and solution could be a key factor that decides how much 6PPD is removed. Therefore, testing pumice's filtration efficacy at a neutral pH is necessary to definitively evaluate its 6PPD removal capabilities. Future work should investigate best practices for 6PPD solution preparation, as 6PPD has a lower solubility in water than 6PPD-q. This means that some of the experimental practices for dissolution and chemical handling outlined by Lane et al. (2024) for 6PPD-q did not work for the 6PPD solution. Acidifying the solution was my solution to this issue, as it was outside the scope of the project for me to test a multitude of other methods.

Dissolution of 6PPD

Though I added acid to the solution to facilitate dissolution, not all of the 6PPD dissolved. Thus, it was difficult to quantify the exact concentration in both the influent and effluent, as a calibration curve for the UV-VIS is most effective when there is an exact, known influent concentration. Also, because I had to make different batches of solution, this meant the concentration of 6PPD differed slightly between column runs. To circumvent this issue, I reported my findings in a percent removal format. This allowed me to nullify any confounding effect that a difference in influent concentration might have created on the amount of 6PPD

removed. This method of comparison is a more robust result that can be compared across each filtration medium, regardless of influent concentration.

Because 6PPD-quinone completely dissolves in water much more easily than 6PPD, I hypothesize that a UV-VIS detection method would be more effective in giving an accurate concentration of 6PPD-quinone. This would be beneficial because findings could be reported in a format that reflects an exact concentration of the solution, rather than using percent removal. More tests should be done with this detection process following the method for a KHP calibration curve by Kim et al. (2016) to further expand the understanding of this detection method.

Experimental Setup

Rather than cycling the 6PPD solution through the filtration media, I chose to run it through once and take a consistent amount of effluent. Because of this setup, I was limited in evaluating how the filtration efficacy of pumice and soil changed over time – the only insight I had to this problem was through the still-water bottle experiments. More research is needed to evaluate how pumice and soil perform with 6PPD filtration over time, which will help evaluate their efficacy if implemented in the field. If soil or pumice stop being effective quickly, this would make them an inefficient real-world implementation. In addition, these experiments were conducted in a lab. Conducting similar tests at field sites is necessary to understand field-based limitations of stormwater filtration by pumice and soil.

Future Work

To evaluate if pumice should be implemented in the field as a stormwater filter for 6PPD and 6PPD-quinone, more work must be done. Though pumice by itself does not filter 6PPD as effectively as HPBRM, it could still be useful. Future analyses should test if adding pumice to HPBRM increases its filtration efficacy and/or lifespan, similar to the work done with biochar by Ihenetu et al. (2025). In addition, this experiment tested pumice's ability to filter 6PPD. Its ability to filter 6PPD-q has not been studied. Further experiments using 6PPD-q instead of 6PPD would evaluate if pumice filters both chemicals, similar to HPBRM, or if pumice has a vastly different effect between the two.

Importantly, the lethal limit of 6PPD-q for Coho salmon is only 0.041 ppb. These experiments tested pumice's ability to filter a solution with a concentration three orders of magnitude higher. Thus, more tests are necessary to see if pumice has an effect on such a small concentration of contaminant. This should be done with both 6PPD and 6PPD-quinone.

HPBRM is an effective filter, but the exact reason for this is still unknown. We know that adding biochar to soil makes it more effective for 6PPD and 6PPD-q filtration (Ihenetu et al. 2025), but there are many characteristics of biochar that could take credit for this performance boost. More research is necessary to evaluate if biochar is effective because of its ability to physically trap contaminants, or because of its ability to chemically bind with contaminants. In addition, the knowledge about biochar's effectiveness with 6PPD and 6PPD-q filtration can help inform future tests on other relevant filtration media.

Further testing should also be done on biochar by itself to see if its presence in HPBRM increases or decreases its filtration efficacy. This should in a controlled manner that is consistent with other experiments like this one. This would enable a direct comparison between biochar and

pumice, which could further inform if biochar is the reason for HPBRM's success as a 6PPD and 6PPD-q filter, or if there is an inherent property within the HPBRM that contributes to its filtration efficacy.

Finally, if any of these filtration media does prove to help lower the concentration of 6PPD and 6PPD-q in stormwater runoff, can last a reasonable amount of time, and can do so in a way that has a negligible effect on the environment, storm drain filters should be manufactured and installed in places where runoff often drains into streams. One example of this is the Seattle metropolitan area, which is densely populated and sees a lot of traffic. This could also be a potential field site for future field-based tests.

Conclusions

The main result of this study shows that pumice is less effective than HPBRM at filtering 6PPD from a solution. In addition, this test provided insight into what specific physical parameters assist 6PPD filtration: the filtration medium must have a large surface area of porous material (which could be inside the clast, outside the clast, or a combination of both) and it must have a high packing fraction to facilitate consistent contact between the solution and the filtration medium. On top of these important physical factors, this research shows that HPBRM has a chemical advantage over pumice. The presence of key cations and organic matter enable more 6PPD removal from HPBRM than seen in the pumice. These findings should be used to investigate new filtration media and refine our current solutions to this environmental issue.

Though pumice is not the perfect solution to this problem, its low cost and moderate effectiveness mean that it has an important role to play in the realm of 6PPD and 6PPD-q mitigation. It might be effective within a mixture, such as an updated version of HPBRM, or it could outlast other filtration media in terms of its useful lifespan. Thus, its practicality could be a key factor that decides its implementation, but the current understanding of this issue is not sufficient to make a decision. In conclusion, pumice shows promise in the 6PPD and 6PPD-q mitigation realm, but more research must be done to find its exact niche and fully protect Coho Salmon, aquatic environments, and human health from this pollution issue.

Appendix A: pH of Each Solution Sample

Table A1. Columns:

sample	pH		sample	pH		sample	pH		sample	pH
control D	1.49		control A	1.32		control B	1.07		Control C (control B waste)	0.91
soil A	2.71		0.5-1mm A	1.32		2-4mmB	1.05		6PPD without HCl	6.25
soil B	1.82		0.5-1mm C	1.35		2-4mm C	1.03			
soil C	1.94		1-2mm A	1.43		4-8 mm A	0.99			
beads A	1.36		1-2mm B	1.34		4-8mm B	0.96			
beads B	1.31		1-2mm C	1.33		4-8mm C	0.91			
beads C	1.27		2-4mm A	1.32						
			mixed A	1.36						
			mixed B	1.32						
			mixed C	1.34						

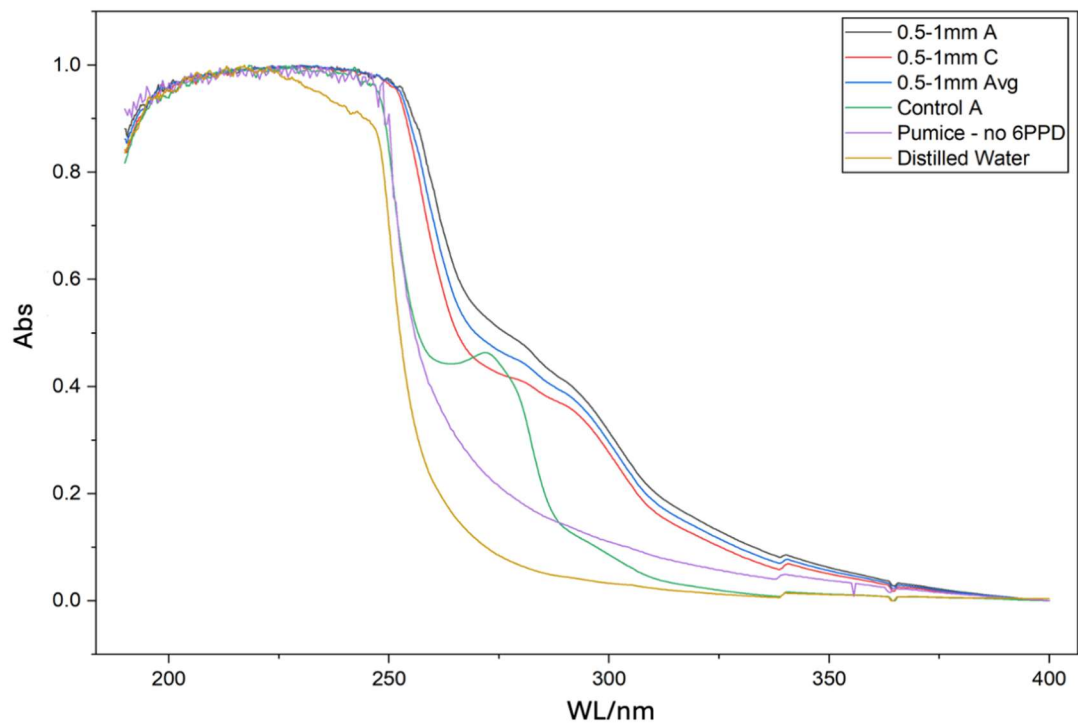
Table A2. Bottles:

sample	pH		sample	pH		sample	pH
control	0.97		control	0.97		control	0.97
soil 30	0.96		pumice 30	0.97		beads 30	0.95
soil 1	0.96		pumice 1	0.95		beads 1	0.94
soil 2	0.96		pumice 2	0.95		beads 2	0.94
soil 5	0.96		pumice 5	0.96		beads 5	0.94
soil 12	0.96		pumice 12	0.96		beads 12	0.95
soil 24	0.97		pumice 24	0.97		beads 24	0.93
soil 48	0.98		pumice 48	0.96		beads 48	0.93

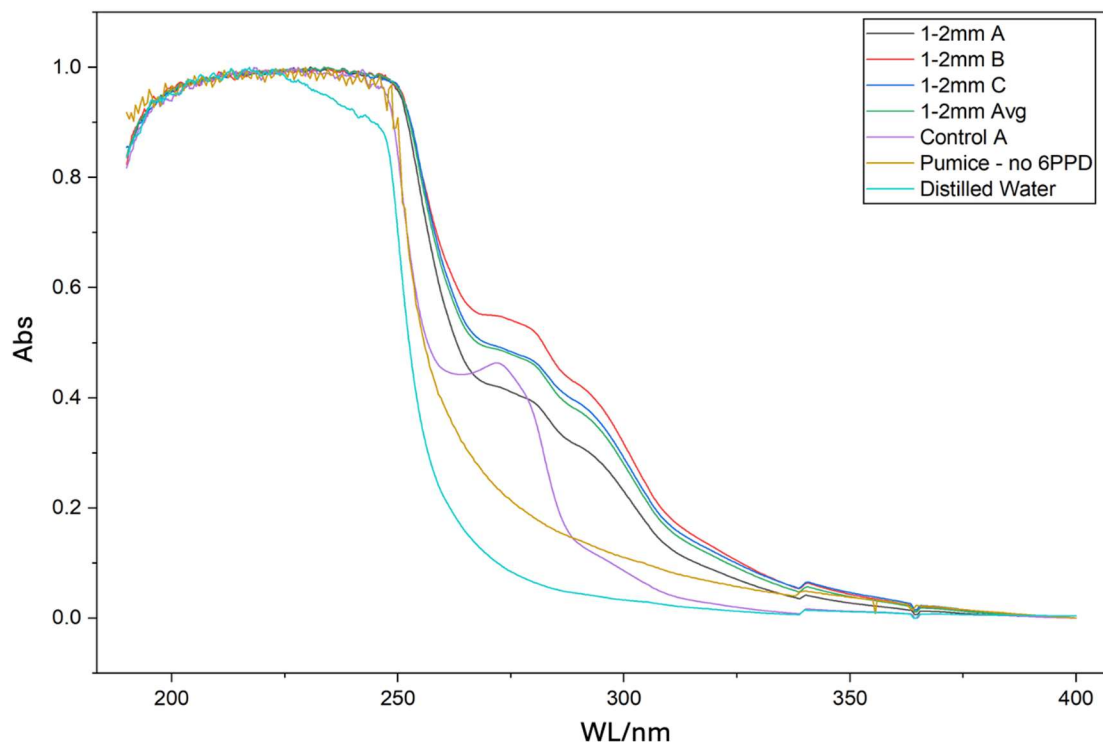
Appendix B: Spectra of Effluent

B1. Column Experiments

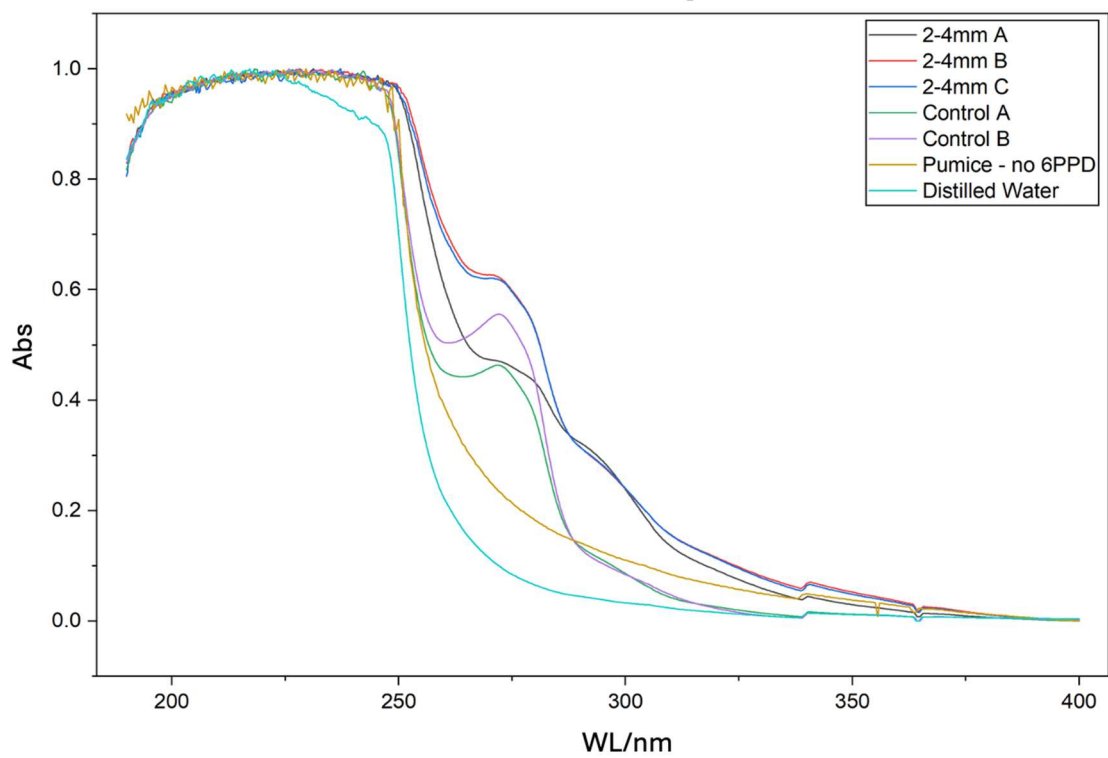
0.5-1 mm Effluent Spectra



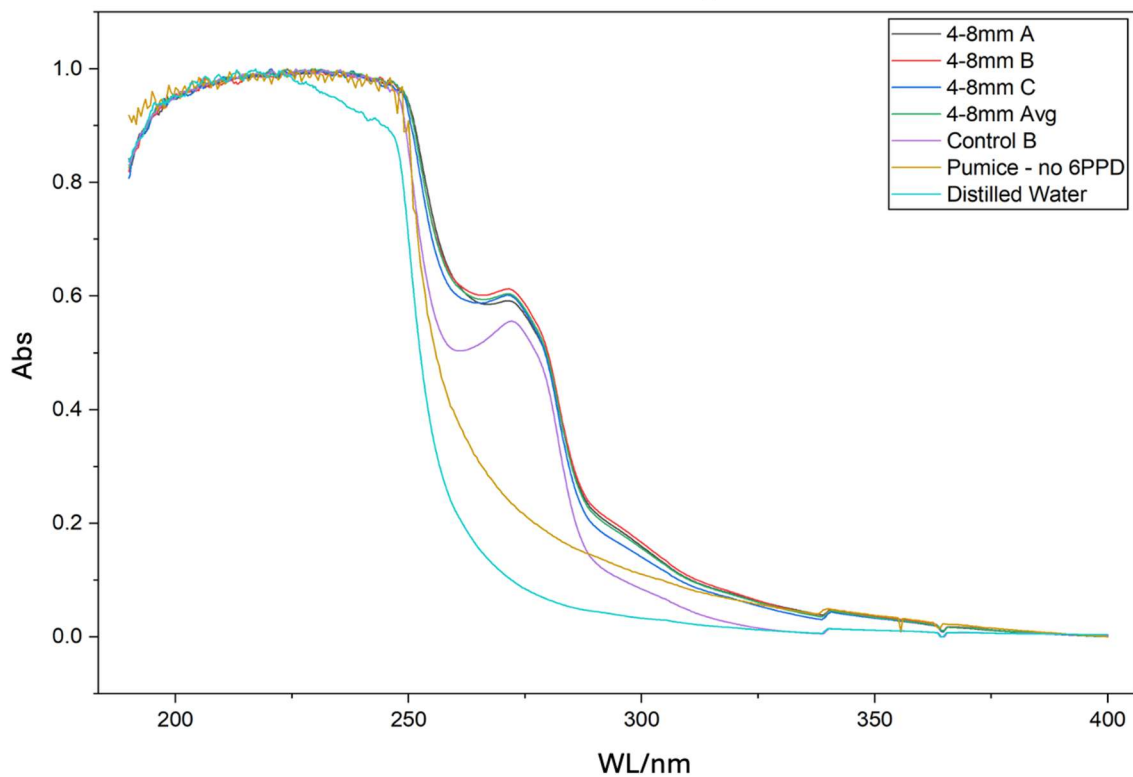
1-2 mm Effluent Spectra



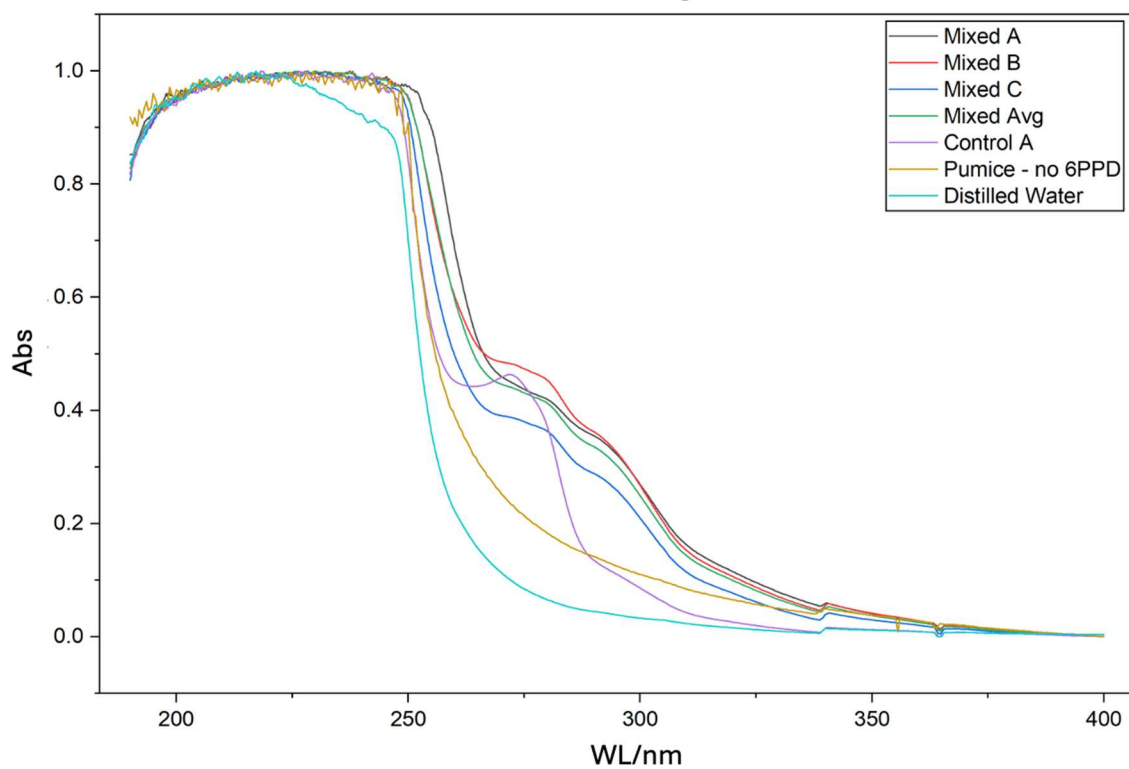
2-4 mm Effluent Spectra



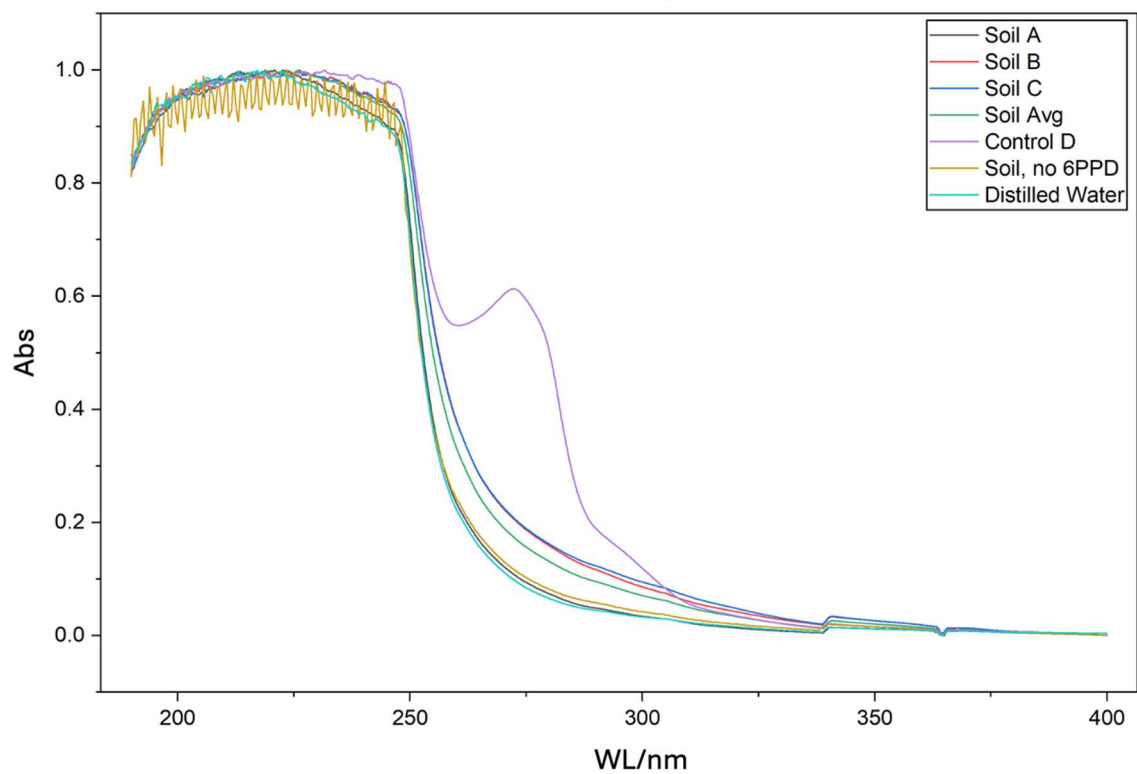
4-8 mm Effluent Spectra



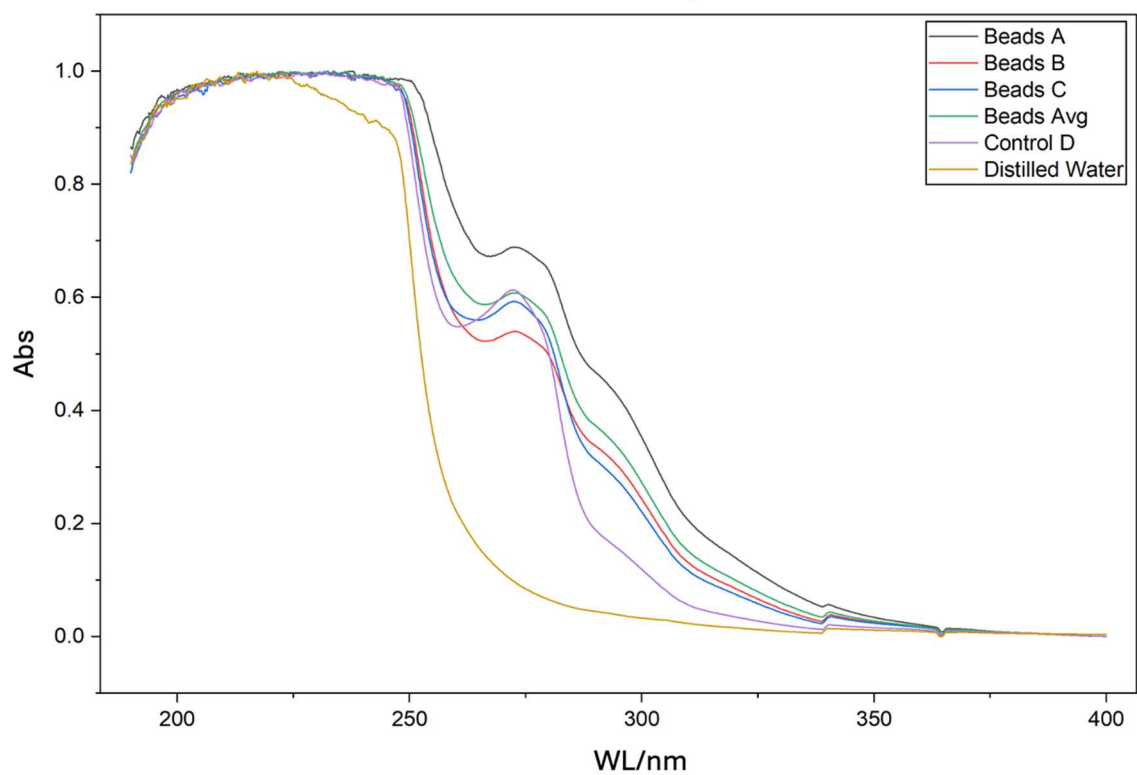
Mixed Effluent Spectra



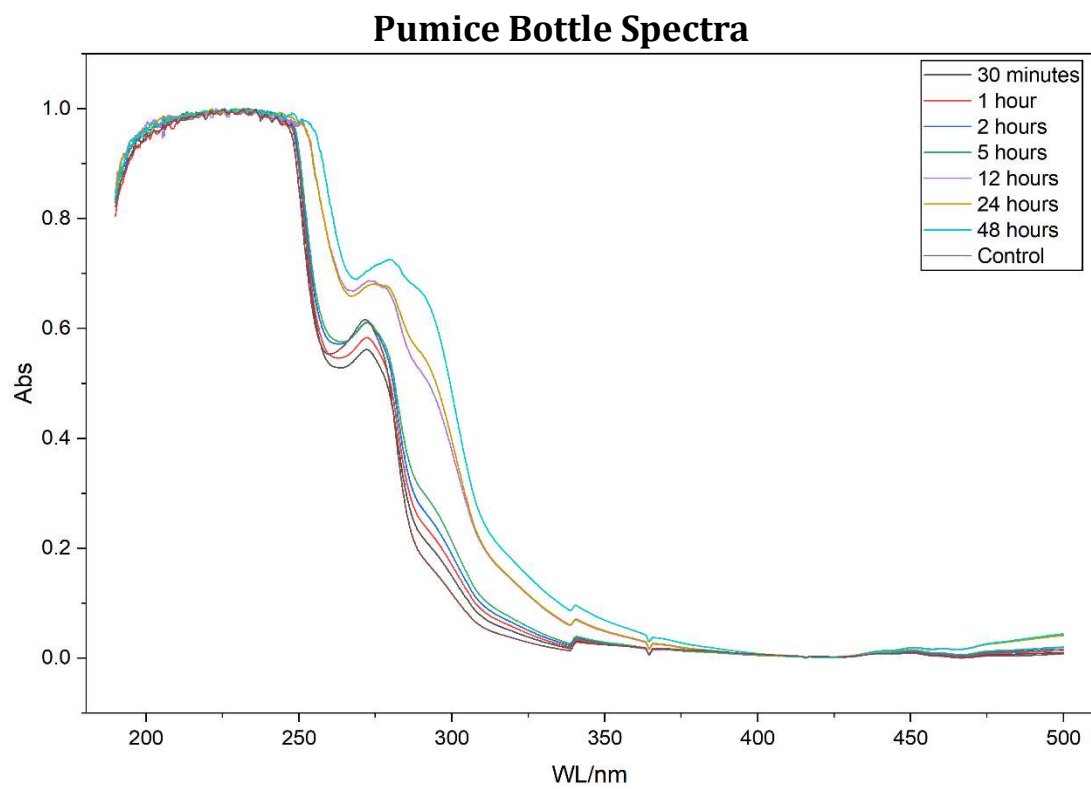
Soil Effluent Spectra



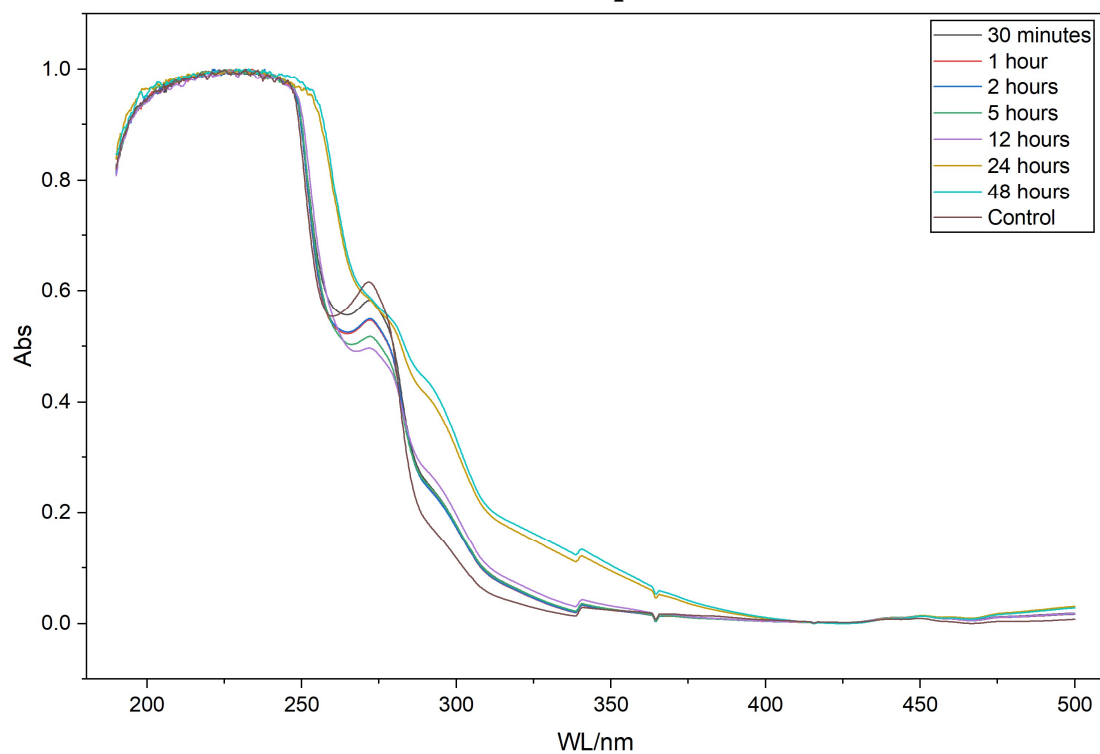
Beads Effluent Spectra



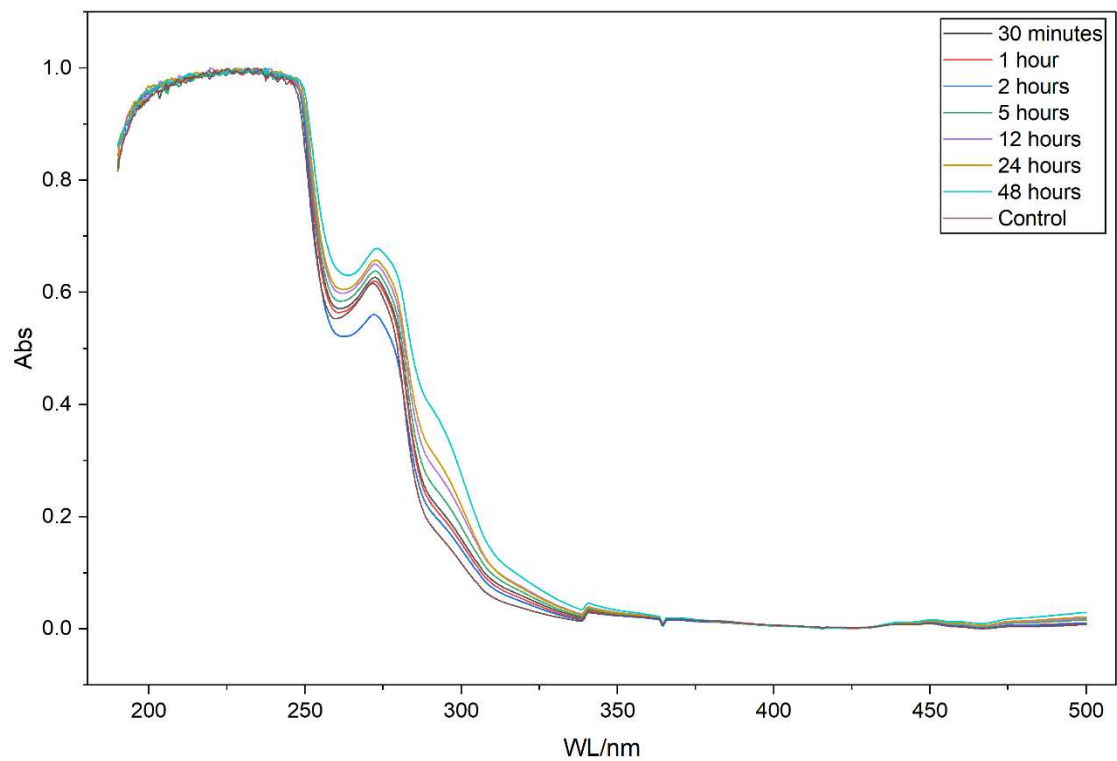
B2. Bottle Experiments



Soil Bottle Spectra



Beads Bottle Spectra



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