Nanotechnology of Foam: Water Filtration

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I. ABSTRACT

In an effort to develop an effective and cheap method of purifying water, experiments were performed to determine the possibility of utilizing sol-gel products as water filtration devices. If sol-gel products were used as water filters, it was theorized that they would be just as effective as simple water filtration units at removing contaminants from water. These materials were compared to common filtering materials in terms of flow rate and extent the amount of contaminants removed. Alone, different filter components did not filter contaminated water well but had much faster flow rates when compared to mixed-media filters.

When combined, the filters work much better than they did alone. Also, they work best when they are organized with fine materials at the top and coarse materials at the bottom. Moreover, alum, a flocculent, purifies the filtrate even further. Sol-gels and foams were also tested as filters, as sol-gels are very porous and are very cheap to create. Unfortunately, neither the foams nor the gels that were tested seem to be viable options for filtration systems because the foams were unable to allow contaminated water to flow through them.

II. INTRODUCTION

Seven hundred and fifty million people are forced to drink water contaminated by viruses, bacteria, and macrocontaminants every day. In countries, especially developing countries, troubled by drought and disease, there is a need for a cheap and efficient way to obtain clean water from unsanitary sources without the use of electricity, thermal energy, or other equipment that is not readily available. Common filters such as the Lifestraw® and Lifesaver® bottle are too expensive for large populations in developing countries to benefit greatly from. It is necessary that a cheaper filter be made so that the majority of people can benefit.

Polluted water sources can include contaminants such as bacteria, viruses, and other waterborne pathogens. Since all of these contaminants vary in size and shape, many different types of filter components are often combined to effectively clean the waters. However, even comprehensive and cheap filtration techniques cannot wholly purge water of small viruses and bacteria. Only a new, alternative filtration method could filter out the smallest viruses and bacteria.

In theory, reducing the pore diameters of filters would limit the amount of contaminants remaining in the water. Viruses are the smallest harmful contaminants; they have a minimum size of 40 nm. The sol-gel process, depending on the specific techniques used, can be a relatively inexpensive means of creating foams with pores as small as 2 nm in diameter. Water molecules are only 2.75 Angstroms (0.275 nm) in length. This specificity is even more effective than the leading commercial water filter, Lifestraw®, which cannot filter the smallest viruses.
III. BACKGROUND
I. The Sol-Gel Process

Sol-gel, the abbreviated term for "solution gel", describes a process used to create porous materials with novel properties such as superhydrophobicity and high thermal insulation. This wide range of possibilities allows the products of the sol-gel process to be applied in many different fields of technology.

The sol-gel process involves the reaction of a precursor, a chemical that contains many elements of the future gel, with a liquid medium. When the two initially react, the molecules create a network suspended in liquid. After some time, which varies depending on the procedure performed, the molecules form an inorganic network and the substance turns into a gel. The gel becomes a continuous, solid shell encapsulating a liquid, formed by the entanglement of polymers within the sol. Finally, when the gel begins to dry, the liquid contained inside evaporates, causing the substance to shrink and turn into a foam.

In particular, gels made of colloidal silica were used for this experiment. As they are generally softer and more flexible than foams, they are easier to create into filters. Moreover, the gels used in this experiment were porous and, therefore, could be used as potential water filters.

II. Nanotechnology of Foam

Foams synthesized using the sol-gel process are extremely porous and lightweight. By using the precursor tetraethoxysilane (TEOS), porous foams are created from the process. In this experiment, some of the foams tested for their filtration properties were not created using the traditional precursor method. By replacing the TEOS with methyltriethoxysilane (MTES), the fabrication process is expedited and creates an aerogel. Aerogels in particular have very large surface areas and very low densities because of their high porosity, with surface areas typically ranging from 600-1000 nm. They also consist of 95% air and have pores ranging from 2-200 nm in size. One noteworthy feature of this method is that it makes superhydrophobic aerogels without subsequent surface modification. Superhydrophobicity, literally "water fearing", refers to the ability of a substance to be extremely hard to wet.

Because of its porous nature, an aerogel can potentially serve as an effective water filter. When contaminated water flows through the foam, contaminants are prevented from passing through, due to their relatively large size.

III. Mixed-Media Filters

Most filter setups tested in this project containing different materials can be classified as a mixed-media filter. Mixed media filters consist of layers of various filtering materials, each with different porosities, densities, and properties. When water flows through a mixed-media filter, each layer removes a certain amount of contaminants, and the end result is a much cleaner water sample. These filters are effective at removing macrocontaminants that are easily separated from the water, but are ineffective at removing microcontaminants that are either dissolved in the water or too small to be trapped by the pores. Mixed media filters were used in this experiment because many commercial filtration systems are mixed-media filters, in addition to the fact that sol-gel products could easily be incorporated into the filtration system. However, it is unclear as to the most efficient way to organize the filter components within a mixed-media filter. Therefore, one component of our experiment involved testing the layout of the filter components within mixed-media filters.

IV. Filtration Procedures

This experiment involved two major steps: testing the filtering properties of various materials, foams, and gels, and then comparing their effectiveness.
I. Filtering Properties

I.1 Testing Sol-Gel Products

To test the filtration properties of aerogels and gels, a number of tests were performed. First, the foams were placed into a plastic funnel with a tight seal so that water would not leak through the sides. Water was then dropped onto the foams with a pipette. Then, another approach was taken to get more results. The spout of a burette was inserted into the top of the foam, and then 1000 mL of water was poured into the burette in an attempt to force the water through the foam.

When testing gels, plastic funnels were sealed at their narrow ends with layers of the silica gel. Three filters were constructed, with one, two, and five layers of gel. The plastic funnels were filled with 10 mL of water and were placed in graduated cylinders.

I.2 Testing Common Filtering Materials

The next part of the experiment involved determining the filtration properties of different filtering components. The different components included coffee filters, charcoal, ceramic beads, fine sand with .15 mm grains, and coarse sand with .37 mm grains. The coffee filters served as the control for this experiment and were placed into a glass funnel. All the other components were placed into glass funnels along with the coffee filters so that the fine particles would stay elevated. The other filtering components were tested individually during separate runs, during which 100 mL of different contaminant solutions were poured through the filters.

The substances used as contaminants were corn starch, dextrose, and plant protein. The contaminated water consisted of 5 mL of corn starch in 95 mL of distilled water, 7.7 g of dextrose in 90 mL of distilled water, and 5 mL of plant protein in 95 mL of distilled water.

The filters were suspended by ring stands and extension clamps. 10 mL of each contaminant solution were funneled through the various water filter components. Graduated cylinders were used to measure the amount of contaminated water that passed through the filter components. Lugol’s solution, Benedict’s solution, and Biuret Reagent solution, which test for starch, sugar, and protein, respectively, were used as indicators to observe the quantities of the different contaminants remaining in the filtrate. The equipment used with those methods included test tubes, test tube stands, and a hot water bath.

I.3 Constructing Mixed-Media Filters

Five different filters were created to research the filtration properties resulting from different mixed-media patterns. The container of each filter was an empty plastic water bottle suspended upside down, with the bottom of the bottle cut off. Filter Setup 1, as shown in Figure 2, contained 45 g of ceramic beads, 50 g of coarse sand, 50 g of fine sand, and 5 g of charcoal, in that order, from the bottom to top of the filter. Filter Setup 2, as shown in Figure 3, contained the same amounts of the same materials, but in the reverse order, with ceramic beads at the top of the filter and carbon at the bottom.
Filter Setup 3 contained 15 g of charcoal, 150 g of fine sand, 150 g of coarse sand, 135 g of ceramic beads, and 150 g of gravel. This filter setup was made in the same order as Filter Setup 2, with added gravel, but the quantity of each material was tripled. The amount of material was increased in order to give the filter a larger surface area for the solution to pass through. For Filter Setups 1 and 2, 50 mL of water were dripped onto the surface through a burette to saturate the filter, and for Filter Setup 3, as shown in Figure 4, 200 mL were dripped onto the surface through a larger burette, to saturate the filter.

Filter Setup 4 consisted of the same materials and had the same order as Filter Setup 3, but without any charcoal in the setup. 200 mL of tea were dripped onto this setup as well. This filter was constructed specifically to ascertain the impact of carbon on the tea, and to determine if any carbon was present in the filtrate of the other setups.

To further determine if the order of filters (pore diameter order) affected filtration, another filter setup was constructed. Filter Setup 5, as shown in Figure 5, was constructed in the reverse order of Filter Setup 3; from top to bottom, the setup consisted of 15 g of charcoal, 150 g of
I.4 Testing Mixed-Media Filters

In the first filter setup, the materials were arranged so that the filter component with the smallest pore diameters was on the top, and the filter component with the largest pore diameters was on the bottom. The other filter setup was arranged so that the filter component with the largest pore diameters was on the top, and the filter component with the smallest pore diameters was on the bottom. The reason for testing two different orders was to ascertain the most accurate and efficient organization of filtering components. The charcoal was considered to have very fine pore diameters, as the round nuggets that compose charcoal have both micropores of 1-3 nm and macropores of 3-10,000 nm.\textsuperscript{15}

A burette then dripped tea into each filter to test the filters’ abilities to separate the chemical components of tea, particularly tannic acid, from the water that the tea was made with. Tannic acid (C\textsubscript{76}H\textsubscript{52}O\textsubscript{46}) is a relatively large polymer that mixes well with water but can still be separated without a chemical process.\textsuperscript{16} Filter Sets 1 and 2 filtered 100 mL each of tea, while Filter Set 3 filtered 200 mL of tea. Another setup, Filter Setup 4, was constructed at this point.

Both Filter Setups 3 and 5 were first saturated with 200 mL of water. Then, 200 mL of a Coca-Cola\textsubscript{TM} and Pepsi\textsubscript{TM} mixture were dripped into each setup. The effectiveness of the filters was determined by observing the color of the filtrates and the pH of the filtrates. These observations were made to see if the filters removed phosphoric acid or Caramel E 150D, the main color of Coca-Cola\textsubscript{TM} and Pepsi\textsubscript{TM}.\textsuperscript{17} The pH of the soda mixture and the total time for filtration were recorded, as well as the pH and color of the filtrate after passing through each setup.

Afterwards, alum, a coagulant, was added to the other filtrates to see the difference in filtrate. 1 g, 1.5 g, 2 g, and 2.5 g of alum each was added to four different quantities of 8 mL of filtrate from Filter Setup 3 in the test involving the Coca-Cola\textsubscript{TM}-Pepsi\textsubscript{TM} mixture.

In order to test the filtration properties of the filters made, solutions containing different contaminants commonly found in unfiltered water were mixed together, and 200 mL were added to each filter. The contaminants used were the same as the ones used in the testing of common filtering materials. All water used was distilled water. Food dye was added as a separate contaminant, as were the Coca-Cola\textsubscript{TM}/Pepsi\textsubscript{TM} mix and tea.

II. Surfactant Hydrophilicity

One of the superhydrophobic aerogels was treated with a solution of polyethylene glycol and titanium dioxide. First, a brush was used to spread a fine layer of the solution on the top of the aerogel. In the end the foam was set upright and drops of the TiO\textsubscript{2}-PEG solution were added onto the surface to be absorbed over a 24 hour period. Titanium dioxide is hydrophilic, so it was placed on top of the gel to see if it would aid in water absorption.
V. Results

I. Filtering Properties

I.1 Testing Sol-Gel Products

When water was first dripped onto the aerogels with a pipette, the water did not pass through the aerogels.

Moreover, when a significant amount of force was applied to the aerogel, water was not able to flow through.

Similarly, the gels absorbed a very minimal amount of water. The filter with 1 layer of gel seemed to allow 10mL of water to pass through in 10 minutes, but then a crack in the seal was discovered and the data had to be discounted. The filter with 2 layers of gel allowed 2mL of water to pass through in about 5 days, and the filter with 5 layers of gel did not let any water flow through.

I.2 Testing Common Filtering Materials

None of the filters completely prevented the starch and sugar contaminants from passing through the filtrate. The protein contaminant was not present in any of the filtrates according to the lack of change in the biuret reagent; however, the biuret reagent solution may not have worked properly. The results for the various solutions to filter through a filter component is listed in Table 1 for starch, Table 2 for dextrose, and Table 3 for protein.

Table 1 - Starch

<table>
<thead>
<tr>
<th>Filter Component</th>
<th>Contaminant present?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coffee Filter</td>
<td>Yes</td>
</tr>
<tr>
<td>Ceramic Beads</td>
<td>Yes</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>Yes</td>
</tr>
<tr>
<td>Course Sand</td>
<td>Yes</td>
</tr>
<tr>
<td>Charcoal</td>
<td>Yes</td>
</tr>
</tbody>
</table>

*Note: Indicator turned from orange to green over time (more to less contaminant), but contaminant still present

Table 3 - Protein

<table>
<thead>
<tr>
<th>Filter Component</th>
<th>Contaminant present?**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coffee Filter</td>
<td>Inconclusive</td>
</tr>
<tr>
<td>Ceramic Beads</td>
<td>Inconclusive</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>Inconclusive</td>
</tr>
<tr>
<td>Course Sand</td>
<td>Inconclusive</td>
</tr>
<tr>
<td>Charcoal</td>
<td>Inconclusive</td>
</tr>
</tbody>
</table>

**Note: Protein indicator did not show presence of protein in any sample, including test of 50% water 50% protein, so indicator is suspected to be expired or defective

I.3 Testing Mixed-Media Filters

Filter Setup 3 filtered about 66 mL of tea and Filter Setup 5 filtered about 82 mL of tea, as shown in Figure 6. Filter 1 was able to filter the tea in sixteen minutes and sixteen seconds, whereas the amount of time Filter 5 took to filter the tea was not recorded because the flow rate was not consistent and therefore not accurate.
appeared to be a slightly paler color of the original mixture. Filter Setup 5 was able to change the mixture's pH from 2.5 to 5 as well. The color of the mixture after passing through the filter was a pale, almost white, liquid. The filtrate from Setup 5 was much paler and overall lighter. Both filters were able to filter the mixture in about the same amount of time – fifty minutes.

When alum was used to clear the murky filtrate from the bottle filters, a clear, honey-colored solution, shown in Figure 8, was obtained that contrasted strongly with the previous opaque appearance, shown in Figure 6. The filtrate was much lighter and clearer, as the finer particles present earlier were no longer in the filtrate.

![Fig 8: Filtrate after alum removed with coffee filter](image)

II. Surfactant Hydrophilicity

The titanium dioxide based coating was never fully absorbed by the foam because of the hydrophobic nature of the foam. The coating remained on top of the foam, and when water was dropped onto the surface of the foam, the water was repelled and formed smaller beads.

VI. Discussion/Analysis

I. Filtering Properties

From the results, it appears that the contaminated water took longer to flow through substances with small pore diameters and flowed faster through substances with large pores. Moreover, the contaminants were still present in most of the filtrate. In the case of protein, the tests were inconclusive. This suggests that the filter components by themselves did not remove different contaminants. In addition, the protein indicator did not show presence of protein in any sample, including in a test of 50% water and 50% protein, so the indicator was suspected to be expired or defective.
II. Reorganization of Different Filters

Removing carbon from a filtration system hinders its filtration properties. When comparing Filter Setup 3 to Filter Setup 4, the filtrate from Filter 4 was much murkier than the filtrate from Filter 3. Often in the form of charcoal, carbon is useful in filtering organic material, such as protists and many microorganisms. In addition, it has a high functional surface area (large area of filtering substance exposed to substance), which is useful as contaminants are more likely to become trapped. One of the negatives of carbon is that the carbon is a likely breeding ground for bacteria, as its moist and dark nature is ideal for bacteria growth. Therefore, carbon filters need to be disinfected after multiple uses, which is one negative concerning their overall usefulness.  

When comparing Filter Setup 1 and Filter Setup 2, it appears that Filter 1 was able to remove more particles than Filter 2 because Filter 1 had less filtrate than Filter 2. This suggests that more particles and contaminated water were trapped within the filter itself. Moreover, when comparing Filter Setup 3 and Filter Setup 5, Filter Setup 5 appeared to remove more particles than Filter Setup 3 because there was less dye in the filtrate of Filter 5 and since Filter 5 seemed to have less filtrate; however, the results may have been skewed due to the presence of runoff water already present in the filter. Therefore, the most efficient arrangement of filter components is from fine to coarse.

Because of faulty burette adjustment equipment, it was difficult to maintain a steady flow of droplets from the contaminant solution in the burette to the top of the filter, so this may have changed the results, as the rate of adding contaminant varied per test.

Using alum as a coagulant for fine particles left over in the filtered solutions proved to be very effective at filtering even more contaminants from the original simulated contaminant mixture. Alum works by attracting fine particles and grouping them together, eventually getting the groups to a size that can be trapped by filters. In this case, the alum coagulated fine particles in tea and soda, and the groups were large enough to be removed by coffee filters.

III. Cost Analysis of Filters

The cost of each filtering component affects the overall price of the filter. Sand of various sizes can cost about $4.15 for forty-eight pounds. 26 250 coffee filter papers cost $7.49. Gravel costs $4.77 for sixty pounds. 30 Carbon powder costs $10 for 6 oz. 29 Four hundred and fifty grams of ceramic beads cost $9.95. 21 Compared to filters such as the Lifestraw®, the filters made during the experiment were much cheaper. While the Lifestraw® costs $31.95, Filter Setups 1 and 2 cost $1.34, Filter Setups 3 and 5 cost $3.98, Filter Setup 4 cost $3.09 to make. 23 Also, the alum adds $0.04 to the filters’ costs. One pound of alum costs is $9.47. Moreover, the silica foams cost $0.96 to make. 18 L colloidal silica cost $346. 28 The silica aerogels cost about $1.50 to make since the Titanium Dioxide costs $27 for one pound.

Filters 1 and 2 (Thin material layers)

\[(45g \times $9.95/450g) + (50g \times $4.15/21772.4g) + (50g \times $4.15/21772.4g) + (5g \times $10/170.097g) + (1\text{count} \times $7.49/250\text{count}) = $1.33\]  (1)

Filters 3 and 5 (Thick material layers)

\[(15g \times $10/170.097g) + (150g \times $4.15/21772.4g) + (150g \times $4.15/21772.4g) + (15g \times $9.95/450g) + (1\text{count} \times $7.49/250\text{count}) = $3.98026\]  (2)

Filter 4 (No charcoal)

\[(150g \times $4.15/21772.4g) + (150g \times $4.15/21772.4g) + (135g \times $9.95/450g) + (135g \times $7.47/27215.5g) + (1\text{count} \times $7.49/250\text{count}) = $3.098\]  (3)

IV. Surfactant Hydrophilicity

Without added chemicals or pressure, the surfactant coating was not absorbed by the foam and had no impact on the hydrophobic nature
of the foam. This coating is not a viable solution without added chemicals that would ensure the absorption of the coating by the foam. With the addition of ethanol or another alcohol, which foam is attracted to, the foam may have absorbed the solution, but without any other chemicals added, the foam’s hydrophobic nature would simply prevent the titanium dioxide solution from being absorbed.

VII. Conclusion

I. The Sol-Gel Method

Although the sol-gel method is useful in quickly producing foams with nanoscale pores, the foams used were ineffective as water filters due to their superhydrophobicity. The foams did not absorb any water, even when the water pressure was increased to 1 L. In addition, since the aerogels were very brittle, passing water through them at high pressures could cause them to crumble and recontaminate the filtrate. Without significant modifications to the foams, they are unable to be used as water filters.

II. Future Research

With limited time and resources, the sol-gel products could not be chemically transformed into more viable filters. However, many possible directions can be taken in the future concerning hydrophobic aerogels and water filtration.

Coating the hydrophobic aerogel could be coated with a more hydrophilic substance. A hydrophilic solution of TiO$_2$, PEG, and other alcohols could be applied to both ends of the aerogel. This would mimic the phospholipid bilayer in biological cells and could increase the efficiency and flow rate of the aerogels used. The hydrophilic coating would draw water into the filter, while the hydrophobic part would filter the water to a large degree due to its small pore diameter. Finally, the water would be able to exit the aerogel via the hydrophilic coating on the other side of the foam. Through this method, the pore diameters would be efficiently utilized, and the hydrophilic additions could help transport water across the filter at a faster rate. This may improve the filtration properties of sol-gels.

The hydrophilic coating could also be made slightly basic in order to increase the pH of the water being filtered. This would render the filter helpful in regions of the world that are infamous for pollution, as contamination tends to make water slightly more acidic. Adding a hydrophilic and basic coating to aerogel filters would neutralize the water acidity of polluted water to a degree safe for consumption. This modification would also be useful in hydroponics and irrigation systems to channel clean water to fresh produce, as plants are very susceptible to changes in water pH as well.

Future experiments could also attempt heating up the aerogels to a maximum temperature of 450 Centigrade, which would increase the pore diameter of the aerogel. This could lead to potential water absorption despite the foam’s superhydrophobicity.

In addition, one could experiment to see the best placement of foams within a conglomeration of filter components. Sol-gel foams could potentially become the final processing unit in a collection of other cheap filters with large pore diameter. The foams are very brittle; exposing them to large contaminants could damage them. Thus, if the foams were to be used in commercial water filters, they would need to be used in conjunction with other filtering components.

Finally, in an effort to create filters that can aid many people in developing nations at a time, perhaps one could design a quick, large scale water filtration system containing silica aerogels. This could be attained by engineering cheap, commercial processes for aerogel production. Moreover, this can be achieved by altering the chemical makeup of the foams and sol-gel production techniques. For example, although we added a solution of titanium dioxide and PEG to our solution, we could have added an alcohol such as ethanol to allow the solution to absorb into the foam. However, since adding an ethanol coating to the foam could contaminate future filtrates, alternatives to alcohol would have to be researched.
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