ABSTRACT

Title of Thesis: SUSTAINABLE GREYWATER FILTRATION ON A RESIDENTIAL SCALE

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This project proposes a sustainable greywater filtration system for residential-scale water reuse. Recycled greywater can be used in toilet water, outdoor irrigation, car washing, and clothes washing, reducing the demand for potable water. Although pilot-scale systems have been demonstrated for greywater recycling, residential-scale applications remain unexplored, as treatment options on a residential scale are limited. This project designed and implemented a residential-scale greywater filtration system into reACT, the University of Maryland's 2017 Solar Decathlon House. The system was constructed within the constraints of the Solar Decathlon, with an emphasis on sustainability. It used several filtration methods, including micron, mineral sand, activated carbon, and ultraviolet disinfection. Multi-phase water testing was conducted to evaluate pH, turbidity, chemical oxygen demand, total organic carbon, and total nitrogen. The prototype proved capable of functioning in a real-world setting and filtering water to meet several non-potable urban reuse standards.

SUSTAINABLE GREYWATER FILTRATION ON A RESIDENTIAL SCALE

By

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List of Abbreviations

ANOVA - Analysis of Variance

BOD - Biological Oxygen Demand

BOD_5 - Five-day Biological Oxygen Demand

COD - Chemical Oxygen Demand

EPA - Environmental Protection Agency

GAC - Granular Activated Carbon

MCF - Membrane Cartridge Filtration

MF - Microfiltration

MSB - Mean of the sum of Squares Between treatments

MSW - Mean of the sum of Squares Within treamtents

MWCO - Molecular Weight Cutoff

NF - Nanofiltration

NOM - Natural Organic Matter

NPOC - Non-purgeable Organic Carbon

NTU - Nephelometric Turbidity Units

OCC - Off-line Chemical Cleaning

OMC- On-line Mechanical Cleaning

OMCC - On-line Mechanical-Chemical Cleaning

POC - Purgeable Organic Carbon

RO - Reverse Osmosis

TN - Total Nitrogen

TOC - Total Organic Carbon

TSS - Total Suspended Solids

UF - Ultrafiltration

UV - Ultraviolet

VOC - Volatile Organic Compounds

Chapter 1: Introduction

The United States uses more water per person than any other country.[1] The average person in the United States uses about 70 gallons (265 L) per day indoors and 30 gallons (114 L) per day outdoors.[1,2] With an increasing world population and changes in agriculture, water withdrawal for most uses, such as domestic, industrial, and livestock, is projected to increase by 50% by 2025.[3] In 2015, 663 million people still did not have access to **improved drinking water sources**.[4] Changes in temperature and increasingly variable weather conditions are projected to impact the availability, distribution, and quality of water.[5] Higher global frequency of droughts also presents additional challenges to traditional water management infrastructure.[6] Water is becoming an increasingly finite resource around the world.

Residential water systems almost exclusively use potable water, meaning water filtered to drinking standards, but over 78% of water usage in homes does not require the water to meet potable standards.[7] For example, potable water is not necessary for landscaping, gardening, irrigation, clothes washing, and toilets. Due to wasted water, the use of potable water where not necessary, and other factors, 40 U.S. states' water managers expect water shortages in some part of their state in the next decade.[8]

Traditional water management infrastructure mixes **blackwater** and **greywater** together in the same stream prior to filtration. Greywater is relatively clean wastewater from baths, sinks, washing machines, and other kitchen appliances, whereas blackwater is wastewater from toilets. The term "greywater" comes from the level of contamination of household appliances' **effluent** relative to blackwater from toilets. This represents an inefficiency in the design of current systems, as the relatively clean greywater could be purified more easily if it were not contaminated with blackwater. Recycled greywater can serve as a valuable to address water needs, while conserving potable water.

This study proposed a residential greywater filtration system that aimed to recycle household greywater for **unrestricted non-potable urban reuse**. Unrestricted non-potable purposes include landscape and market crop irrigation, air conditioning, toilet flushing, construction, vehicle washing, and environmental enhancement. Recycling greywater for non-potable uses can both preserve potable water and improve the sustainability of individual households. By reducing the amount of potable water consumed, fewer resources and less energy will be used in the production of potable water. For every one million gallons of potable water conserved, almost 1,500 kWh of energy is saved.[1] Although energy on this order of magnitude may not appear significant, it is one of many inefficiencies that should be addressed. A case of greywater reuse in Australia resulted in cost savings, reduced sewage flows, and saved up to 38% of potable water.[9] In Arizona, one study found that the average household generates 30,000 to 40,000 gallons of greywater per year, suggesting that greywater is a significant potential source for water conservation.[9] Although there is significant literature on rainwater recycling, there is limited research on the efficacy of greywater recycling on a residential scale. The team explored the potential for residential-scale greywater recycling to address water management needs and promote sustainable design and more efficient use of resources.

The team approached this challenge in two phases: the design phase and the testing phase. In the design phase, current and upcoming filtration techniques were assessed with an emphasis on selecting environmentally friendly filtration elements. Based on this literature review, the team designed a filtration system aimed at recycling greywater to unrestricted non-potable urban reuse standards. The water filtration system uses **ultraviolet (UV) disinfection** and physical filtration methods, including **micron filters**, a **Next Sand** filter, a **ceramic filter**, and a **granular activated carbon (GAC) filter**.

After the prototype of the system was completed, it was implemented into the University of Maryland's submission for the Department of Energy Solar Decathlon Competition, reACT, which won second place in the 2017 competition. The team continued to iterate on the design following the competition. Filters were replaced and some were upgraded to more efficient models. Changes were made to the plumbing to streamline water flow, improve water pressure, and incorporate newer filtration and measurement elements. After these modifications were completed, the team transitioned into the testing phase.

In this phase, water quality testing was conducted on municipal water and synthetic greywater, both prior to and following treatment. The Environmental Protection Agency (EPA) specifies potable water standards with over 90 water quality parameters, but it does not provide regulatory values for non-potable water.[10,11] For the purposes of evaluating the proposed water filtration system, seven water quality parameters of interest were identified: pH, **turbidity**, **chemical oxygen demand (COD)**, **biological oxygen demand (BOD)**, **total organic carbon (TOC), total nitrogen (TN)**, and bacterial load.

During the testing phase, municipal and synthetic greywater samples were run through the filtration system. pH, turbidity, COD, TOC, and TN measurements were collected first for both treated and untreated municipal water, and then for treated and untreated greywater. The results indicate that the filtration system is capable of meeting several non-potable urban reuse standards.

Chapter 2: Literature Review

Greywater recycling methods can be broken down into three categories: physical, biological, and chemical. Physical filtration processes leverage characteristics of the greywater such as particle size and weight, making them most effective at removing large particulates and reducing turbidity.[12] **Sedimentation**, which removes the heaviest solids from incoming greywater, is typically placed at the beginning of the water filtration process.[13] Another common method of physical filtration is membrane filtration, which removes particulates on the basis of size. The efficiency of membrane filters is dictated by the size of their pores, which range from macroscale to nanoscale.[12] A drawback of physical filters is that they must be periodically backwashed, cleaned, or replaced due to fouling, which incurs financial and time costs for maintenance.[12]

Biological filtration techniques use microorganisms to improve the quality of wastewater by consuming most organic and some inorganic pollutants in the water.[14] Biological filtration methods are infrequently used on their own, as they are usually preceded by sedimentation or screening and followed by chemical filtration because both biological and chemical filtration require low turbidity to effectively kill pathogens.[12] Examples of biological filtration technologies include **biosand filters** and **trickling filters**. Biosand filters consist of a traditional sand filter with a bacterial layer on top, called a **biofilm** . The sand acts as an additional physical filter, while the bacterial layer decomposes organic matter. Biosand filters can remove organics and solids that were not removed by previous filters.[12] Trickling filters enable organic pollutants to be decomposed by microorganisms in a biofilm.[15] Trickling filters typically require periodic maintenance and may develop an odor due to solids buildup over time.[15] Both biosand filters and trickling filters typically include **aerobic** and **anaerobic** bacteria.[12]

Chemical filtration techniques induce chemical changes in the pollutants through the addition of various chemicals.[14] Chemical disinfection mechanisms are typically placed at the end of filtration systems to kill remaining microorganisms and prevent regrowth, as they do not remove particulates and other pollutants.[14] The placement of disinfection at the end of filtration is strategic because the greywater has already been purged of particulate matter that would otherwise shield microorganisms.[16] The most common chemical disinfection technique is **chlorination**.[12] The use of chlorination must be controlled because excessive residual chlorine can be hazardous to human health.[17] A potentially safer option is ultraviolet disinfection, which uses UV light to kill microorganisms without altering other water quality parameters. UV disinfection does not require the synthesis, transportation, and consumption that chlorine does, making UV disinfection more environmentally friendly. Another chemical filtration method, **coagulation**, can be implemented earlier in filtration systems, working in conjunction with physical treatments. Coagulants can be added to inlet greywater to cause pollutants to stick together, forming large masses that can be more easily removed via physical filtration.[14] Despite the effectiveness of chemical filtration techniques, they must be used with caution to avoid dosing the water beyond levels that the filtration system can safely handle.

Testing Parameters

The EPA lists regulations for more than 90 different contaminants in water.[11] Substantial resources would be required to quantify the levels of these contaminants;

however, the general cleanliness of water can be gauged using seven measurements: pH, turbidity, COD, BOD, TOC, TN, and bacterial load. These measurements can encapsulate a substantial portion of the contaminants that the EPA regulates in just a few tests.

The ideal pH of drinking water is between 6.5 and 8.5.[18,19] While pH is important in determining how corrosive a water sample is, dissolved gases, colloidal matter, and other materials in water also determine the extent of corrosion in a system.[18] Generally, as pH decreases, the potential for corrosion increases.[18] Corrosive water can lead to the release of hazardous metal ions from piping materials, such as iron, manganese, copper, lead, and zinc. There are also health hazards associated with water with a pH above 8.5 because a high pH can cause adverse effects on the water's odor, color, and appearance.[18]

Turbidity, measured in nephelometric turbidity units (NTU), is an indication of the clarity of water.[20] A turbidity of less than 10 NTU is considered normal for unagitated rivers, and a turbidity of less than 0.3 NTU in 95% of samples is listed as an EPA regulation for drinking water.[11] High levels of turbidity indicate particulate matter in the water which causes light to be scattered, making the water appear cloudy or opaque. While moderate turbidity is aesthetically unappealing, it does not have a direct impact on human health.[20] The real hazard lies in the microorganisms that are shielded by the particulate matter in water, making them less likely to be inactivated. If left untreated, turbid water can become a breeding ground for potentially harmful pathogens. Once large particulate matter is effectively removed, chemical treatment or ultraviolet disinfection can effectively kill the remaining microorganisms and render the water safe to drink.

Chemical oxygen demand quantifies the amount of oxygen that can be consumed by chemical reactions per volume of water.[21] COD tests use chemicals to oxidize almost all organic compounds. Standard COD testing protocols use a solution of potassium dichromate which is incubated with sulfuric acid.[22] The COD test is non-specific, meaning that it is not able to differentiate the identities of the compounds it oxidizes.[21] COD testing usually takes a few hours, providing quicker results than BOD_5 tests, named for their testing period of five days.[21] BOD is similar to COD, as it measures the possible consumption of oxygen by a volume of water. However, BOD only quantifies the biologically oxidizable chemicals, rather than all material capable of being oxidized, which means that BOD values are always less than or equal to COD values.[21] Raw wastewater and treated wastewater typically exhibit BOD:COD ratios of 0.5:1 and 0.1:1, respectively.[23]

Total organic carbon encompasses all of the organic material measured by COD tests and additional non-oxidizable organics.[21] While TOC tests account for more than COD tests, TOC measurements on their own are not sufficient to characterize the oxygen demand in water. This is because TOC cannot differentiate between compounds with the same number of carbons in their molecular structures.[24] For example, ethanol and oxalic acid both have two carbons in their structure, but the oxygen demand of ethanol is six times larger that of oxalic acid.[24] TOC testing is performed by inserting a sample into a total organic carbon analyzer where the sample is heated, which oxidizes the carbon in the sample to CO_2, which is then analyzed using nondispersive infrared sensing to determine concentration.[25] Following this, acid is inserted into sample, which is heated up. The CO_2 measured after acid addition is the inorganic carbon, and can be subtracted from TOC measurements. In environmental sampling, non-purgeable organic carbon (NPOC) is used instead because there is a large quantity of inorganic carbon, which may interfere with measurement of organic carbon. Instead of inserting acid into the sample following the measurement of organic carbon, sparging occurs first, causing the removal of inorganic carbon as well as a small amount of purgeable organic carbon (POC). Compared to the precision lost due to the high volume of inorganic carbon in the standard TOC procedure, the removal of POC in the NPOC procedure is negligible. Following the removal of POC and inorganic carbon, the amount remaining is recorded as NPOC.[25]

Total nitrogen is a measure of the nitrogen present in organic nitrogen, ammonia, reduced nitrogen, nitrates, and nitrites.[21] In natural water bodies throughout the US, values accepted as safe for the ecosystem for TN range from 2 to 6 mg/L.[11,26] Accepted values of nitrates in drinking water vary upwards of 10 mg/L, which is the US standard.[27] For testing purposes, the team began with a value of 10 mg/L as the target, keeping in mind the more stringent environmental reuse recommendations (as low as 2 mg/L). The Shimadzu method collected data for the same sources of nitrogen as the Kjeldahl method, which was previously the predominant method for data collection on nitrogen concentrations.[28] These sources were organic nitrogen, found in proteins, as well as nitrates/nitrites and ammonia which provide much of the biochemical driver of water chemistry.[28–30] A main failing of the Kjeldahl method of collection was its low recovery of nitrates and nitrites. The Shimadzu method resolved this problem, recovering all tested compounds, including nitrates/nitrites, ammonia, and organic nitrogen at over 90% recovery rate.[28]

Testing for TN is done using a Total Organic Carbon Analyzer with the Total Nitrogen add on. Samples containing nitrogen are inserted into a chamber at 720℃, causing the formation of nitrogen monoxide. In the next chamber, nitrogen monoxide is combined with ozone to create NO_2 and NO_2^*, an excited form. The return of NO_2^* to the ground state is used to determine the types of nitrogen present. The amount of each type of nitrogen seen is compared to values seen for standards created beforehand.[28,31] Testing for TN is quick and useful for determining pollution, particularly from microorganisms. This testing methodology fails to capture the presence of organic nitrogen, which can compose a significant fraction of the overall nitrogen within the water. Therefore, TN might better be defined as inorganic nitrogen within the water, mainly ammonia, nitrates, and nitrites. When considering regulation of non-potable water, the presence of additional organic nitrogen may be an important metric to consider.

The most common health risk associated with water is the presence of pathogens.[21] Thus, it is critical that a water treatment system be able to remove microorganisms completely, even if the water is not intended for ingestion. Bacterial load is monitored by plating a water sample in cell media and assessing its presence and growth. Plates must be handled carefully to ensure the samples are not contaminated by microorganisms that were not originally in the water, so as to not influence the results.[21]

Sedimentation

Sedimentation is a physical treatment process that typically follows coagulation, although it can be employed without any pretreatment. During sedimentation, water enters a rectangular settling tank with a single inlet and outlet. The inlet water is slowed to a low velocity so that suspended solids sink to the bottom of the tank.[13] This is especially useful after coagulation because as small particles stick together, the increased size and weights accelerate sinking to the bottom of the tank.[13] About 25-50% of BOD, 50-70% of **total suspended solids (TSS)**, and 65% of oil and grease can be removed during the sedimentation process.[32] However, contaminants that are dissolved or have a low specific gravity will stay suspended in the water. Thus, these pollutants are not effectively removed and must be isolated using another mechanism, such as pumping the water through a micron filter.[14]

The solids that accumulate at the bottom of the tank are called primary sludge, and usually take up about three to five percent of the inlet water.[14] Therefore, it is necessary to remove primary sludge from the sedimentation tanks. There are several removal techniques, such as installing mechanical equipment that continuously cleans the bottom of the tank or manually removing the sludge and cleaning the tank at regular intervals.[14] Sedimentation is almost always used as a primary filtration technique, despite its inability to remove small particulate matter, chemicals, or bacteria.[14]

Coagulation

Turbidity, TSS, and **natural organic matter (NOM)** are major indicators of water quality. Greywater contains significantly elevated levels of turbidity and suspended solids relative to clean drinking water.[33] The concentration of NOM varies significantly from source to source, so the NOM presence in greywater is difficult to generalize. Nevertheless, the major contributor of organic chemicals in residential greywater is **surfactants**, so the concentration of NOM is determined by detergents and soaps chosen within the house.[34] NOM is also known to degrade the effectiveness and flow rate of membrane filters.[35,36] Therefore, reducing NOM concentration early in a filtration pathway will benefit downstream micron filters. Additionally, turbidity will negatively affect the performance and maintenance schedule of a biosand filter.[37,38] Therefore, the removal of turbidity and

NOM serves a two-fold purpose of purifying the water and improving the efficiency of other filters.

Coagulation relies on grouping chemicals together into particle-sized agglomerates. These agglomerates then form a sludge of congealed particles, which must be removed from solution via physical filtration techniques.[36] Typically the removal of coagulated solids is achieved via sedimentation or dissolved air flotation, both of which provide phase separation between bulk solids and liquids to facilitate solids scraping.[39] This process operates via the addition of inorganic salts, typically composed of aluminum or iron, which dissociate in the water and generate positive metal ions. These ions interact with **colloids** and NOM in the water, leading to coagulated particles that can be more easily treated.[35,40] Due to this mechanism, coagulation best treats water for turbidity, TSS, pathogens, and NOM, which subsequently improves the operating efficacy of both biosand and membrane filters downstream.

There are many factors that affect the efficiency of coagulation, such as the mixture of coagulants used, coagulant dose, pH, temperature, **influent** water quality, and properties of the particulates and NOM.[36,41] Therefore, it can be difficult to practically match the efficiencies achieved in laboratory settings.

Table 1 offers an example of the effects of aluminum and ferric salts as coagulants on greywater produced from showers. Both forms of coagulant reduce turbidity by about 90%, significantly reduce COD and BOD, and reduce the presence of several tested bacteria by more than 99.9%.[42]

Table 1: Contaminant Concentrations Following Treatments with Different Greywater Treatment Systems

Optimum	Raw	MIEX® 10 mg/L, 30min	Alum 24 mg/L, pH 4.5	Ferric 44 mg/L, pH 4.5	MIEX® + Al 5 mg/L, pH 4.5	MIEX® + Fe 5 mg/L, pH 4.5
Turbidity (NTU)	46.60	8.14	4.28	5.20	3.01	3.30
COD (mg/L)	791	272	287	288	247	254
BOD (mg/L)	205	33	23	30	27	29
DOC (mg/L)	171.4	78.2	93.4	87.4	78.8	80.7
TN (mg/L)	18	15.3	15.7	17.9	15.3	17.4
NH_4^+ (mg/L)	1.2	1.1	1.2	1.2	1.2	1.2
PO_4^{3-} (mg/L)	1.66	0.91	0.09	0.06	0.11	0.13
Total coliforms (MPN/100 mL)	56500	56	<1	<1	<1	<1
Escherichia coli (MPN/100 mL)	6490	8	<1	1	<1	<1
Fecal *Enterococci* (MPN/100 mL)	2790	<1	<1	<1	<1	<1

Adapted from Pidou et al, 2008[42], table 3. Shower greywater characteristics post-treatment for the systems at optimum conditions.

A relatively new form of coagulation is **electrocoagulation**. Soluble metal anodes of aluminum or iron are placed in the water. A current is passed through the water between the anode and cathode, causing the anode to dissolve metal ions for coagulation and driving the release of hydrogen gas at the cathode, which helps to float the coagulated particles to the surface.[36,43] To improve the conductivity of the water, low concentrations of NaCl can be introduced prior to the electrocoagulation stage.[43–45] Electrocoagulation can also function to increase the pH of raw water.[45] The benefits of electrocoagulation are reduced handling of chemicals, reduced sludge formation, and slightly improved efficiency relative to chemical coagulation.[36,46] A pilot-scale version of electrocoagulation was implemented in a large, individual building, where greywater was treated for non-potable reuse. The quality met recommendations for reclaimed water stipulated by various nations, and this pilot plant achieved profitability, estimating a payback period of 5.5 years.[47]

Biosand Filtration

Biosand filtration is an aerobic and anaerobic filtration process capable of removing physical and biological pollutants from contaminated water.[48] In a typical biosand configuration, layers of fine sand, coarse sand, and gravel fill a plastic or concrete container. Water is filled just over the height of the solids, with a biofilm forming on the uppermost surface of the sand-water interface. The thin biofilm layer typically forms on top of the fine sand layer and allows for biological decomposition. A diffuser plate is placed between the lid and the standing water layer to prevent incoming water from disrupting the bacteria. The fine sand is used to trap particulate matter flowing through the system. The layer of coarser sand below the fine stand prevents the fine sand from entering the outgoing pipe below. Finally, a layer of gravel supports both layers of sand and allows for water to flow through the outlet pipe without pushing sand into it. The outlet pipe travels along the side of the tank and drains above the height of the biofilm to ambient conditions, such that the height of the water in the filter never drops below the solids. Biosand filtration has been found to reduce turbidity to as low as 1 NTU and reduce bacterial and protozoan concentrations by 80-99%.[37] Moreover, it has been found to reduce viral load by 70-99% in laboratory conditions.[37] It typically has a flow rate of up to 0.6 L/min, depending on system sizing, which would allow for over 375 liters to be filtered in one day, even with a recommended recharge period of six hours. Currently, there are a few drawbacks to biosand filters, including the weight, need for frequent cleaning, and declining efficiency over long-term use.[49] The biosand filter can take up to one month to prepare because the biofilm needs time to fully develop.[37]

Trickling Filter

The trickling filter is a biological filter designed to remove organic matter from wastewater. This filter is composed of microorganisms that live on rocks or other solid media, which also allow organic matter to accumulate.[15]

One advantage of this filter is that it is easy to install and operate. It is also relatively inexpensive, as it is made up from rocks or slag and a biofilm. Trickling filters are effective against organic material, thereby reducing BOD and COD provided the biofilm is grown on the right type of medium.[15,50] Trickling filters are also highly durable and require little energy.[15]

One of the downsides of trickling filters is their incubation period of several days, which is required for microorganisms to grow on the media.[51] While this could be a problem for new systems, proper planning can ensure the microorganisms have enough time to grow. Another disadvantage is that the system requires regular attention from a semi-skilled operator.[15] This could be problematic for a trickling filter implemented in a residential setting, as the owner would need a working knowledge of the system and would have to maintain it carefully. Trickling filter maintenance requirements also lead to a relatively high clogging frequency.[15] Additionally, there are odor problems associated with trickling filters.[15] With proper precaution and containment factors these problems can be mitigated, if not removed.

Reverse Osmosis

Osmosis is the diffusion of water across a semipermeable membrane from areas of low solute concentration to areas of high solute concentration. This process requires no external input of energy and occurs spontaneously because it is thermodynamically favorable. The movement of water across a membrane to areas of higher solute concentration creates an osmotic pressure and tends to equalize solute concentrations on either side of the membrane.

In **Reverse Osmosis (RO)**, an external pressure is applied to counteract this osmotic pressure and force water across the semipermeable membrane from areas of high solute concentration to areas of low solute concentration.[52,53] This is the opposite of the natural tendency of the system to move toward thermodynamic equilibrium.[52,53]

RO systems generally have a pore size of 0.1 nanometers, making them extremely effective at removing protozoa, bacteria, viruses, and common chemical contaminants found in water.[54] RO systems are the standard for advanced water filtration and are capable of reducing COD by 99.9%, TSS by 99.8%, and dissolved salts by 99.9%.[54]

Despite being highly effective at removing contaminants, RO water filtration systems have several drawbacks. RO relies on mechanical filtration with a membrane that accumulates contaminants and particles, which can build up and inhibit water flow. As a result, large amounts of water must be used to flush the membrane, resulting in contaminated brine. Although efficiencies are higher in large scale facilities, residential RO systems waste a vast majority of filtered water.[53] RO systems release 4 to 20 L of briney wastewater for every liter of filtered water produced.[55] Moreover, if leftover brine is fed back into the system for filtration in order to increase system efficiency, the membrane life decreases drastically, resulting in higher maintenance costs.[53] In addition to substantial water waste, RO filtration systems are expensive both to produce and install, negating their utility in a residential setting.

Membrane Filtration

Another method of water filtration is membrane filtration, which uses a thin layer of semi-permeable material capable of separating substances when pressure is applied across the membrane.[56] This membrane can remove microorganisms, particulate matter, and organic matter responsible for color, odor, and various tastes within water.[56] The most common forms of membrane filtration are **nanofiltration (NF)**, **ultrafiltration (UF)**, and **microfiltration (MF)**.

NF membranes are most commonly used to soften **hard water**.[57] Processes requiring NF include desalination or softening, a technique used to remove ions such as magnesium and calcium from water.[58] NF membranes do not allow valence ions, organic matter, or salts to pass through, thus softening the water. Because NF membranes do not remove dissolved substances, they are not sufficient alone for water purification. NF membranes are widely used in the reverse osmosis water treatment process. Seeing as reverse osmosis is expensive to use at a residential scale, it is not feasible to use NF systems in residential settings. [57,59]

UF membranes are the next largest membranes with pore sizes of 0.01 to 0.05 microns. They are designed to remove particulates and microorganisms and generate filtrate with turbidity below 0.1 NTU.[60] A special measurement system, known as molecular weight cut off (MWCO), has been instituted to classify the particulates removed by the membrane based on molecular weight rather than size. The standard MWCO level for UF is between 10,000 and 50,000 Daltons. Most membranes used in water treatment only filter down to 100,000 Daltons.[58]

MF membranes contain pore sizes of 0.1 to 10 microns and are mainly used for removal of colloidal and suspended particles through a similar sieving mechanism to UF.[58] Most MF filters can remove pathogens such as giardia, cryptosporidium, and some bacteria.[58] This is all contingent on the nominal (average) size of the pores. Smaller MF filters can remove most of the three pathogens listed above.

Membrane Cartridge Filtration (MCF) systems operate similarly to MF and UF systems because they use sieving mechanisms to remove particles from water.[58] However, MCF uses filtration media capable of removing particles of 1.0 micron or larger.[58]

The **Spin-down Filter,** also known as Spin-out Filter, is a filter that uses an easily cleaned and reusable polyester or stainless steel filter screen.[61] This filter is mostly found in the market with three pipe sizes: 1”, 1.5”, and 2”, which are designed to handle progressively higher flow rates.[61] Spin-down filters operate at a maximum pressure of 150 psi, which is more than enough for residential homes that typically do not exceed 60 psi water pressure. As spin-down filters continue to operate, their pores become clogged with debris, eventually blocking water flow. Moreover, filtered particles settle to the bottom of spin-down filters. To purge the settled sediments, spin-down filter come with a flush valve that allows for a quick removal of the contaminants. Additionally, to maintain the efficiency of the spin-down filter, the polyester or stainless steel filter is cleaned regularly (depending on the load and run time) in order to remove the solid particulates from the pores. Between the purge valve, which removes loose particulates and the washable nature of the membrane, spin-down filters require infrequent replacement when handling residential greywater. Spin-down filters trap large particles while supporting higher flow rates, making it sufficient for pre-screening greywater in residential homes.

Ultraviolet Disinfection

Ultraviolet (UV) disinfection can be incorporated into water filtration systems to kill the pathogens present in the water.[16] UV disinfection incapacitates microorganisms by damaging their nucleic acids, so they can no longer function.[62] UV filters can incapacitate bacteria, viruses, and protozoan cysts.[62] Seeing as UV disinfection does not use chemical compounds, it does not change the composition of the water.[59] Because UV disinfection only inactivates microbes and does not physically remove them, the microbial remains continue to contribute to the organic carbon and organic nitrogen loads.

For mercury-based UV lamps, the UV dose, a measure of the filter's effectiveness, depends on the mercury vapor pressure.[62] Mercury lamps used in UV filters usually operate under either low or medium pressure. Low pressure lamps have a longer bulb life; however, medium pressure lamps require fewer bulbs to achieve the same UV dosage.[62] Ballasts are used to regulate the current and voltage needed by the lamps. Ballasts are either magnetic or electronic.[62] **Electronic ballasts** provide continuous changes in lamp intensity, whereas **magnetic ballasts** can only apply step changes in intensity.[62] Electronic ballasts, however, are more susceptible to problems with power surges.[62]

The effectiveness of UV disinfection is greatly reduced by the presence of large particulate matter in the water.[16] Therefore, it is essential to reduce turbidity and suspended solids in water prior to treating it with ultraviolet radiation.[64] In addition, chemicals, such as calcium, iron, and other contaminants found in water can foul the surfaces of components of the UV filter system, particularly the outer quartz sleeve.[62] The buildup of these contaminants can decrease the effective dosage of the UV lamp into the water.[62] Although temperature, pH, and alkalinity do not reduce the effectiveness of UV disinfection itself, they can cause contaminants to build up more quickly on the outer sleeve of the UV filter.[64] Lamp sleeve cleaning methods can be used to combat this fouling.[62] For large scale systems there are typically three sleeve cleaning methods: off-line chemical cleaning (OCC), on-line mechanical cleaning (OMC), and on-line mechanical-chemical cleaning (OMCC).[62] In OCC systems, the lamp is turned off, drained, and then a cleaning solution is put through it.[62] Both OMCC and OMC systems use wipers that move along the lamp sleeve.[62] OMC and OMCC systems do not require the lamp to be drained; thus, they are on-line systems.

Next Sand Filtration

The Next Sand filtration method uses a mineral referred to as Next Sand that is highly processed and graded. It is a high purity clinoptilolite that offers characteristics of granular media filtration. Clinoptilolites are a natural **zeolite** that are used in water filtration for their unique absorption, catalytic, ion exchange, and molecular sieve properties.[65] Clinoptilolites are low-cost compared to other granular media filtration methods.[65] Next Sand media provides three areas of possible improvement relative to typical multi-media filtration methods: turbidity reduction, service flow rate, and ease of use.

Next Sand media is rated for a **nominal filtration** rating of 3-5 microns.[66] Normal multi-media filtration is rated for a nominal filtration of 8-15 microns.[66] The Next Sand media is also effective in decreasing turbidity levels. Typical multi-media can reduce the turbidity of feed water from 200 to 150 NTU.[66] However, Next Sand media can reduce the turbidity of feed water from 200 to 50 NTU.[66] Another possible advantage of Next Sand media is a greater flow rate of up to 12-20 gpm/ft^2.[66] Normal multi-media filtration only allows for a flow rate up to 3-10 gpm/ft^2.[66] Additionally, Next Sand media is capable of being backwashed, which involves reversing the flow through the system to allow for purging the media of previously filtered material.

Granular Activated Carbon Filtration

The primary role of GAC within water purification is to improve the taste and smell of water, which is why Brita filters are composed primarily of activated carbon.[67] However, there is additional utility in GAC media aside from removing taste- and odor-producing compounds. GAC can also remove volatile organic compounds (VOCs), NOM, synthetic organics, and various disinfection byproducts.[68] Therefore, GAC can be incorporated into a water filtration system to assist with nonpolar contaminants.

The main contributor of organic chemicals in residential greywater is surfactants, introduced by detergents and soaps within the house, which can be mitigated by GAC treatment.[34] Activated carbon filters are a suitable solution for treating greywater to non-potable standards.[69] GAC is able to reduce BOD values by 97%, COD by 94%, TOC by 97%, surfactants by over 99%, TN by 98%, total phosphorus by 91%, and fecal coliforms by 91% (Table 2).[69]

Table 2: Charcoal Filter Reduction in Contamination Level

Parameter	Concentration in influent (mg/L)	Percentage reduction in effluent
BOD	425 ± 56	97 ± 3
COD	890 ± 130	94 ± 2
TOC	304	97 ± 0
TN	75 ± 10	98 ± 1
Total Phosphorus	4.2 ± 0.2	91 ± 8
Fecal Coliforms	$1.73 \pm 3.3 \cdot 10^5$	91 ± 11

Reduction of select parameters in charcoal filtration Dalahmeh et al, 2012.[69]

In another test, a batch adsorption process of three different types of GAC demonstrated roughly 90% removal of anionic surfactants and over 95% removal of non-ionic surfactants.[70] In a tabulated list of GAC adsorption capabilities, GAC was deemed "excellent" at removing cleaning compounds, detergents, disinfectants, organic chemicals, soaps, and a plethora of other common chemicals.[71]

GAC filters operate as a packed bed of particles through which the water passes. This media adsorbs the organics and other nonpolar compounds. Once a sufficient number of contaminants are adsorbed, the GAC becomes saturated.[72] Further removal of contaminants is then inhibited, which is why a large surface area is imperative, enabling longer operating times before media replacement. Conventional activated carbons (mostly coal products) have surface areas of 10-200 m^2/g.[73,74]

Typically, the GAC media is derived from coal or charcoal, but it can also be generated from more sustainable materials, such as coconut shells.[75] There are more than just environmental benefits to coconut shell GAC. For example, laboratory-grade coconut shell GACs can have surface areas as high as 2000 m^2/g, but commercially available coconut shell GACs typically have surface areas around 1100 m^2/g.[73,76,77] Modern-day bituminous coal GAC products are comparable with respect to specific surface area and some adsorption properties.[78] However, when comparing their water purification abilities, coconut shell GAC typically outperforms coal-based GAC. Coconut shell GAC has up to 50% more micropores (< 2 nm) relative to bituminous GAC, improving its ability to absorb VOCs.[79,80] In addition, coconut shell GAC is typically harder and leaches less ash and dust into the water.[79,80]

Production of Synthetic Greywater

The production of synthetic greywater is necessary to evaluate the effectiveness of the prototype water filtration system.[81] Ideal synthetic greywater emulates the composition of average residential greywater and is consistent across multiple batches.[81] The makeup of real residential greywater is highly dependent on the location of the household and the chemical composition of municipal water, meaning different synthetic greywater compositions may be more or less representative of residential greywater depending on the greywater source that they are attempting to reproduce.[81] Hourlier et al.[81] proposed a synthetic greywater composition and compared their proposed formulation to actual residential greywater. The proposed composition is shown in Table 3. This composition is designed to emulate contamination from the human body, shampoo and shower gel, soap, deodorant, tooth paste, shaving and moisturising cream, make-up, and make-up remover. This study compared the proposed composition, other proposed compositions, and actual residential greywater by evaluating them based on pH, conductivity, turbidity, suspended solids, COD, BOD, total coliforms, fecal coliforms, and enterococcus.[81]

Table 3: Synthetic Greywater Formula

Product	Purity	Function	Concentration (mg/L)
Lactic Acid	>85%	Acid produced by skin	100
Cellulose	>90%	Suspended solids	100
Sodium Dodecyl Sulfate	>85%	Anionic surfactant	50
Glycerol	99%	Denaturant, solvent, moisturizing agent	200
Sodium Bicarbonate	>99%	pH buffer	70
Sodium Sulfate	99%	Viscosity control agent	50
Septic Effluent		Microbiological load	10

Synthetic Bathroom Greywater Composition proposed by Hourlier et al. [81]

Table 4 shows the evaluation of both the model synthetic greywater and residential greywater collected from five households in northwestern France from both urban and rural areas.[81] Based on this comparison, the authors of this study concluded that their proposed composition for model greywater is accurate and valid for the purpose of evaluating the performance of water filters.[81] Table 5 shows other synthetic greywater compositions proposed by Diaper et al.[82], Fenner and Komvuschara[83], and Jefferson et al.[84]

Table 4: Comparison of Synthetic Greywater to Real Greywater

	Synthetic Greywater	Real Greywater
pH	6.3	7.2
Conductivity (µS/cm)	163	382
Turbidity (NTU)	24	31
COD (mg O_2/L)	464	258
BOD_5 (mg O_2/L)	63	115
Fecal coliforms (CFU/100 mL)	$7.9 \cdot 10^3$	$3.6 \cdot 10^6$
Enterococcus (CFU/100 mL)	$2.5 \cdot 10^3$	$2.0 \cdot 10^4$

Analysis of Synthetic and Real Greywater prior to filtration proposed by Hourlier et al.[81]

Table 5: Comparison of the Composition of Three Greywater Formulae

	Diaper et al., 2008		Fenner and Komvuschara, 2005		Jefferson et al., 2001	
Chemical Substances	Secondary effluent	20 mL/L	E.coli culture	15 mL/L	Tertiary effluent	2.4 mL/L
	H_3BO_3	1.4 mg/L	Amylodextrine	55 mg/L	Synthetic soap	64 mg/L
	$C_3H_6O_3$	28 mg/L	Dextrine	85 mg/L		
	Na_2PO_4	39 mg/L	K_2SO_4	4.5 mg/L		
	Na_2SO_4	35 mg/L	Na_2CO_3	55 mg/L		
	$NaHCO_3$	25 mg/L	NaH_2PO_4	11.5 mg/L		
	Clay (Unimin)	50 mg/L	NH_4Cl	75 mg/L		
Commercial Products	Deodorant	10 mg/L	Yeast extract	70 mg/L	Shampoo	0.8 mL/L
	Shampoo	720 mg/L			Cooking oil	10 µL/L
	Laundry	150 mg/L				
	Sunscreen or moisturizer	15 or 10 mg/L				
	Toothpaste	32.5 mg/L				
	Vegetable oil	7 mg/L				

Synthetic Greywater Composition proposed by Diaper et al.[82], Fenner and Komvuschara[83], Jeffereson et al.[84]

In another study, the stability of synthetic greywater was evaluated over multiple storage times.[85] The study showed that its proposed synthetic greywater composition was relatively stable with the exception of changes in BOD and nitrate-based nitrogen.[85] Contaminant levels were evaluated immediately after the water was produced, after 48 hours of storage, and after seven days of storage.[85]

Rainwater Harvesting

Rainwater is a common source of drinking water throughout much of the world. Currently, there exists no federal legislation on rainwater harvesting and as of 2010, there were only ten states with related legislation.[86] Across nearly all state and federal guidelines for the harvesting of rainwater, the primary purpose is to offset the load of drinking quality water wasted on appliances like washing machines, toilets, and non-kitchen sinks.

The physical act of harvesting rainwater becomes complex quickly. The water collected is taken from an outdoor roof and then purified to potable standards. In a study of harvested rainwater in a domestic environment, the quality of the collected rainwater with regards to its physicochemical parameters was found to be appropriate for greywater domestic use.[87] The same samples of water were also analyzed to determine their safety for human consumption. The implementation of a **first-flush** system improved the physicochemical quality of the water but failed to avoid microbial contamination within the stored water.[87]

As previously referenced, a first-flush system improves the quality of the water being harvested. First-flush refers to the concept of discarding the first water collected during a rainfall event in order to remove the physical debris and dirtiest water from being routed to the tanks and filtration units. Typical physical debris that could clog the water flow are leaves, sticks, acorns, dust, pollen, etc. However, the first-flush also removes bird or small mammal feces as well as deceased organisms on the roof. Also, the quality of a rainfall harvest is at its worst at the beginning of a rainfall event.[88] Literature and commercial installations ubiquitously support first-flush mechanisms; however, it is still not certain exactly what amounts of water should be diverted under various scenarios.[87–90] When it comes to the first-flush amount there is some general consensus, but the values offered as appropriate amounts of water to redirect are all fairly vague and heavily dependent on location and the number of days since the last rainfall.[88] First-flush values suggested are from 0.4 liters to 0.8 liters per square meter, another suggests 0.4 liters per square meter as a minimum, and after at least three dry days, 2 liters per square meter.[88–90]

Solar Decathlon and Team Maryland's reACT House

The Solar Decathlon is a biennial collegiate competition hosted by the U.S. Department of Energy. It is comprised of 10 contests that challenge student-led teams to design and build an environmentally sustainable home powered by renewable energy. The 10 contests are in architecture, market potential, engineering, communications, innovation, water, health and comfort, appliances, home life, and energy.[91] The competition has advanced technologies and solutions in the international residential building industry.[91]

The University of Maryland has participated in this event four times since the competition started in 2002. Most recently, the University of Maryland formed a team for the 2017 Solar Decathlon competition. This team was composed of both undergraduate and graduate students from various schools at the University of Maryland. All together the team came to develop the reACT house. reACT stands for Resilient Adaptive Climate Technology.[92] The house was designed to adapt and respond to diverse communities and ecosystems. Team Purify worked together with Team Maryland on the reACT house, specifically focusing on the water reuse system and plumbing.

reACT's specific goal in regards to water was to convert both captured rainwater and greywater to unrestricted non-potable urban reuse standards, which was used in the house's hydroponics system. Inputs to the filtration system included the bathroom sink, shower, washing machine, and rainwater. All of these inlets were directed straight to the greywater tank due to space constraints. Ideally, rainwater and greywater should be filtered separately, but, in the final design, the rainwater was used to dilute the greywater. The rainwater was collected from the roof of the house and run through a first-flush system as described before.

The house itself had constraints in regards to available space. The mechanical room was only 5'-8 ⅛" by 5'-5". Not only was it a small space but the electrical and mechanical components of the house had to be situated in the mechanical room as well. The filtration system only had 120 V outlets available for use, which limited the selection of electrical components such as the pump and UV filter.

Chapter 3: Methodology

Problem Statement

Potable water is becoming an increasingly scarce resource. In 2015, 28.5% of people lacked safely managed drinking water services.[93] Water needs are projected to increase while changes in weather and agriculture are projected to lead to a decrease in water availability.[3,5] Most current water management techniques fail to utilize greywater as a potential solution to water needs and a means to conserve potable water. Areas without developed water management infrastructure could benefit from water filtration systems that act independently on a residential or community scale. Although there is substantial literature on the efficacy of rainwater recycling, limited research exists on water filtration systems designed to filter greywater to non-potable urban reuse standards.

Residential-scale greywater filtration is a potential solution to issues with water scarcity. This study was conducted in two phases: a design phase and a testing phase. The aim of the design phase was to develop a sustainable greywater filtration system capable of filtering synthetic greywater to non-potable urban reuse standards. These standards were defined based on a synthesis of the existing state regulations and guidelines for non-potable unrestricted urban reuse. The testing phase of this study aimed to evaluate the capabilities of the system to filter water to the defined non-potable unrestricted urban reuse standards.

Design Considerations

The filtration system was designed for the express purpose of being implemented within the 2017 University of Maryland Solar Decathlon house, reACT. In order to meet the criteria outlined by the U.S. Department of Energy, various design constraints and compromises had to be negotiated. The primary constraint in system development was the application space: a small residential house. Consequently, the filtration system had to occupy minimal space. The system also had to be specified for operational flow rates and volumes amenable to a two to four person household. External engineering and space limitations were placed on the design of the filtration system by various equipment and operational systems in the mechanical room. In addition, the system had to function without supervision and without the use of any chemical purification methods. These constraints immediately eliminated the possible incorporation of coagulants or chlorine within the system.

Wastewater recycling and rainwater harvesting methods were implemented to help achieve net-zero water usage within reACT, which were spearheaded by team Purify. A composting toilet was selected, which removed the only blackwater stream from the house. General water conservation practices were also implemented, such as low flow devices. The removal of toilet effluent reduced the water streams within the house to potable water, rainwater, and greywater. Because there are many documented cases of rainwater harvesting for potable use, the major challenge confronting the team was greywater filtration.[94]

Preliminary Design

Based on the design criteria set out for the team, residential greywater treatment to potable standards became the initial goal. One method to achieve this goal was using RO, which is more than capable of meeting potable standards; however, the team wanted to avoid RO due to the high costs of purchase and maintenance, as well as the wastewater it produces.[52,59] The absence of literature regarding small-scale greywater recycling to potable standards indicates the intractable nature of the problem. Through consultation with a wastewater engineer, the production of potable water without RO was also determined to incur exorbitant costs. However, commercial “under-sink” RO systems would not be feasible, as their flow rates and lifetimes fall significantly below the required values for a greywater treatment system. Consequently, the team designed a filtration pathway, which mirrored small commercial systems, with upstream filtration of particulate matter to extend the lifetime of the RO membrane.

Nevertheless, the complications associated with excessive RO waste streams remained unaddressed. The ratio of potable water to wastewater had been assumed close to unity throughout the preliminary design sketches, as commercial RO systems do not list a waste fraction. During the literature review of RO, this assumption was proven false. Typical residential RO systems operate with a ratio of roughy 7:1 waste water to purified water, although the driving force of high pressure systems can improve this ratio.[95] If the household produced 75 gallons of greywater per day (the initial consumption estimate for reACT) at most only 10 gallons would be reconstituted to potable water for the subsequent day. In this scenario, at least 65 gallons per day of rainwater would also need to be collected and filtered to potable standards to reach net-zero water usage. This would necessitate a second set of pumps, pipes, tanks, and filters, which would interfere with the space constraint. Such a system only makes sense in a climate that consistently experiences rainfall that is more than 85% and less than 100% of the required potable water supply. Only in this optimal range is RO filtration of greywater both sufficient and necessary to achieve a net-zero water balance.

Trickling filters were also considered in preliminary designs. Trickling filters are optimal for rapidly reducing BOD and organics.[15] Although trickling filters are a simple, reliable, biological process, they are mostly used for large scale water filtration. They also require occasional maintenance, as the incidence of clogging can be relatively high.[15] For these reasons, the team decided against using trickle filtration.

Non-Potable Design

In an effort to recycle as much greywater as possible, the team compromised and selected unrestricted non-potable urban reuse standards as the new target. By settling for non-potable reuse, greywater produced within the house could be used for outdoor irrigation, washing cars, flushing toilets, and washing clothes.[93] Due to the limited space available within the mechanical room, the team had to combine harvested rainwater and greywater streams into one filtration system. As the production of potable water directly from rainwater could no longer be achieved, the goal of net-zero water was technically infeasible; however, as long as the volume of rainwater harvested surpassed the consumption of potable water, the team could practically achieve net-zero with a two-stream filtration method for greywater and rainwater.

The primary water quality metrics of interest were turbidity, TSS, bacterial load, COD, pH, TN, and TOC. To reduce these parameters to acceptable levels, the initial design included micron filters ranging from 100 microns to 1 micron in pore diameter, GAC media, and a UV filter. However, concerns regarding bacterial load, turbidity, and surfactant removal led to the incorporation of a biosand filter in the design. The biosand filter introduced numerous complexities and manual labor. Because the biosand filter could not be constructed in a pressure vessel, it was not included in the final design. In its place, a ceramic filter was added, which could remove more than 99.9% of bacteria and was nominally rated for filtration down to 0.5 microns.[96] Nevertheless, the main role of the biosand filter, specifically the removal of soap in the form of surfactants, was unsolved by the ceramic filter. Household surfactant levels are highly variable across different sources and within the same source across samples, with an average load of 17.5 mg/L.[97] A Next Sand filter was added for the purpose of reducing turbidity, prolonging the membrane life of the one micron filter, and crucially assisting with the surfactant load.

Final Design of the System

The main considerations for hardware selection, in order of preference, were performance, sustainability, and price. A filter element was only purchased if it met the design criteria, allowed for some form of reuse or sustainable sourcing, and remained within the team's budgetary constraints. Commercial products were tested against these considerations before their purchase could be justified for prototype testing. An example of this methodology in practice wass the selection of piping material used for the purification system. Most any material would have met the performance necessities, so the decision came down to sustainability and pricing. Fully recyclable polypropylene piping was chosen over PVC or copper due to the environmentally friendly nature of the material's disposal. Aqautherm brand piping provided a polypropylene option within the budget, so it was selected over the cheaper PVC counterpart despite equivalent functionality.

Final System

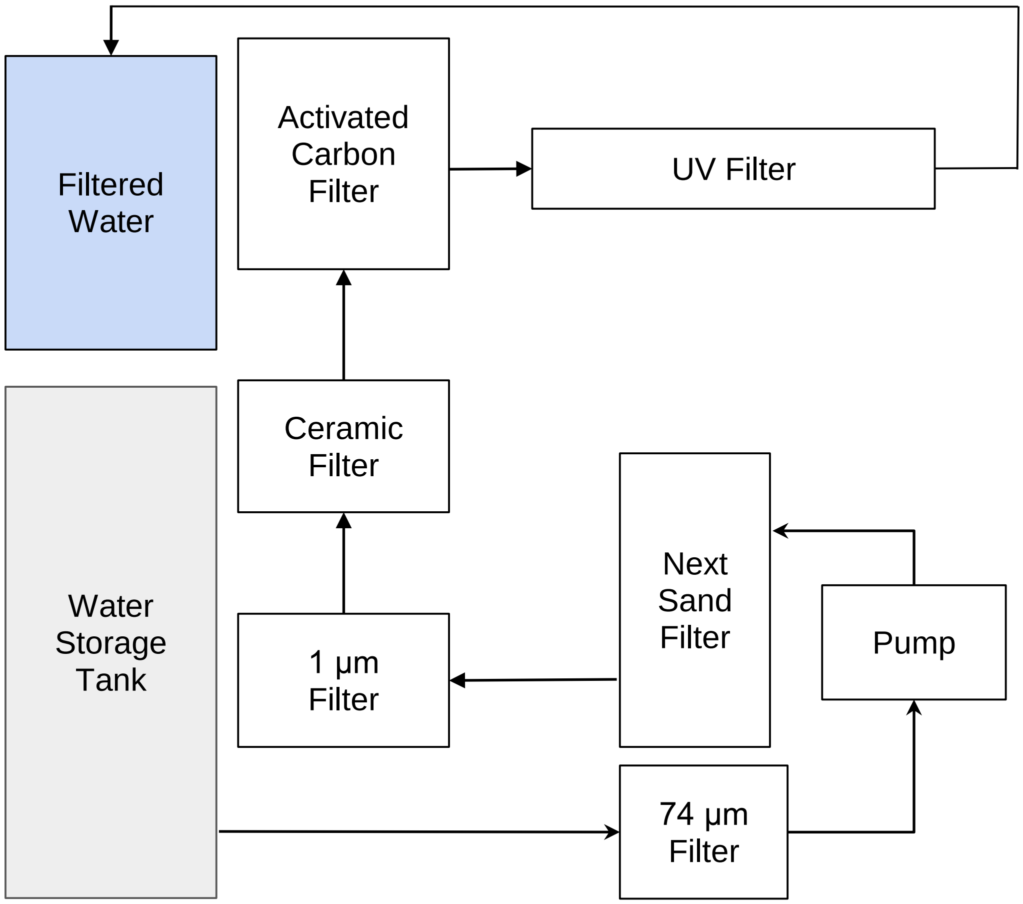


Figure 1: Schematic showing the flow of water through the filtration system.

Figure 2: Assembled filtration system.

The final system schematic appears in Figure 1 and a picture of the system is shown in Figure 2**.** The first method of filtration within the system is the spin-down micron filter prior to the pump, which removes large particulate matter that may otherwise clog the pump (Figure 3B).

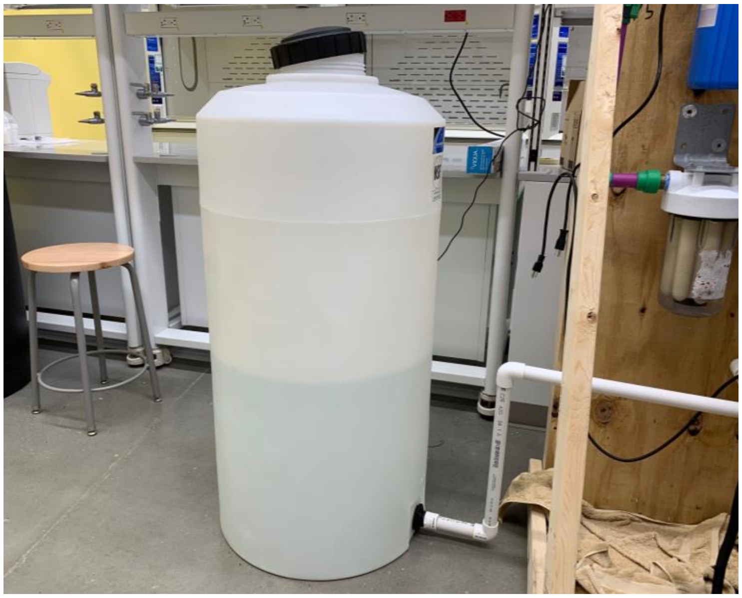


Figure 3A: Inlet Tank (Used for municipal water then later greywater).

Figure 3B: Rusco Spin-Down Filters (74 microns).

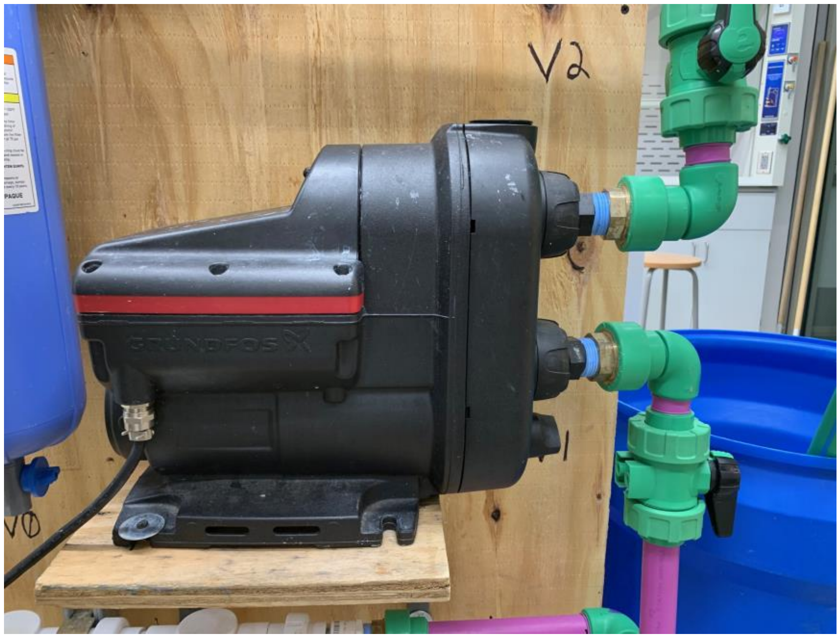


Figure 3C: Grundfos SCALA2 Pump.

Figure 3D: Next Sand Filter.

Figure 3E: One Micron Bag Filter.

Figure 3F: Ceramic Filter.

Figure 3G: GAC Filter.

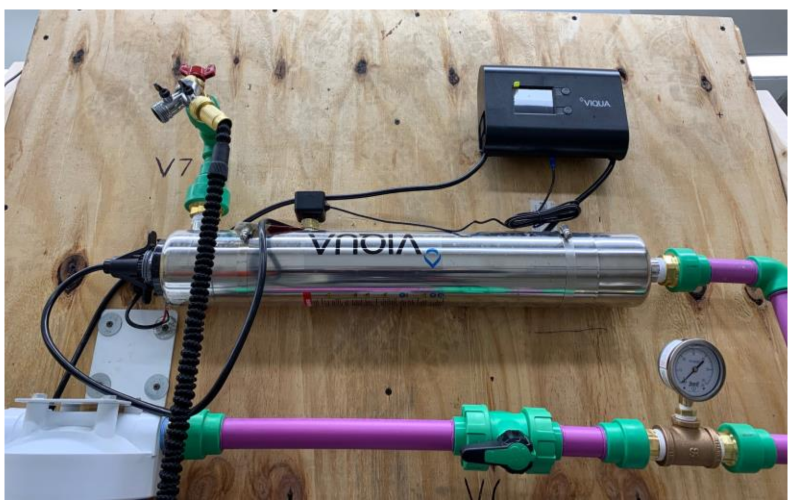


Figure 3H: UV Filter.

The pump must be capable of pulling water through an upstream filter and pressurizing the water through multiple downstream filters. Following the pump, the water flows through a large, pressurized Next Sand filter before passing through a 1 micron bag filter and a ceramic filter (Figure 3D-3F). Next, the water passes through a large GAC filter, providing a similar function to a Brita filter (Figure 3G). Finally, the water flows through a UV filter, killing any remaining pathogens before release (Figure 3H).

Rusco Spin-Down Filters

Rusco spin-down filters offer several benefits over other membrane filters. One important advantage is that they cover a wide range of filtration ratings. Initial design iterations included multiple Rusco filters prior to the pump; however, this design was altered to reduce the inlet pressure requirement for the pump. As such, the final prototype only incorporates a single spin-down filter directly before the pump.

The team decided to use the spin-down filters to catch particulate matter entering the system from the raw greywater. The four filter ratings of the initial design were 140 mesh (104 microns), 250 mesh (61 microns), 500 mesh (30 microns), and 1000 mesh (15 microns), all made from polyester membranes. The filters were placed in decreasing micron size to ensure that larger particulates were caught in the coarser filters, inhibiting membrane fouling of the finer filters. However, in the final prototype, a single 200 mesh (74 micron) metal filter was implemented upstream of the pump, yielding a lower pressure drop. Dropping from four sequential micron filters to one single filter element decreases the filter life, for which the metal (rather than polyester) membrane compensates.

The Rusco spin-down filter also enables easier practical maintenance. It has a clear cover, allowing the user to observe membrane degradation and purge the reservoir when filled. Rusco filters also have a unique centrifugal spin-down technique that traps sediment in the bottom reservoir of the filter housing.[61] As a result, the purge valve at the bottom of the filter can discharge accumulated particulates and the filter does not need to be washed as frequently as other designs.

One downside of Rusco spin-down filters is that they are manufactured with PVC piping, so the connections must be with other PVC components. This means that the system cannot be completely composed of recyclable materials, unless custom-made Aquatherm were purchased. Although PVC was used in the final design, it was only for a small portion of the system. After interfacing the filter with PVC, an Aquatherm-to-PVC adapter was implemented.

Grundfos SCALA2 Pump

The two major restrictions for the system's pump were that it had to operate at 120 V and pull water from a large depth. The 120 V constraint was placed on the system by the reACT electrical team, and the ability to pump water from a reservoir stemmed from the need of a greywater storage tank underneath the house. A 240 V pump would have provided greater power, which would have enabled greater outlet flow rate and pressure. It also may have eliminated the need to remove some of the Rusco spin-down filters upstream of the pump. Grundfos SCALA2 (Figure 3C) was chosen for several reasons: it was quiet, run-dry capable, efficient, and capable of pulling water from a depth of eight meters.[98] The team was also able to obtain a discount from the manufacturer to demonstrate their new pump.

Next Sand Filter

The Next Sand filter is a large pressure vessel that is roughly two-thirds filled with fine gravel and Next Sand media, which is an absorptive mineral sand with ion exchange capabilities.[65] The most important factor in choosing Next Sand media was the integrated pressure vessel form factor, which was compatible with the existing prototype hardware. This setup enabled high flow rates without user supervision and with minimal maintenance as it required infrequent backwashing. In addition, the material was advertised as a means of reducing the presence of surfactants and other soap byproducts. Next Sand has a filtration performance of less than 5 microns and a high flow rate capability in larger vessels.[65] The selected vessel also has a timer module that notifies the user when the system requires backwashing.[65]

One Micron Filter and Ceramic Filter

The 1 micron filter (Pentek BP-420-1) and ceramic filter (Doulton Rio 2000) are key components of the filtration system. The 1 micron filter is a simple bag filter that operates identically to the spin-down filters. This bag filter physically removes particulate matter larger than one micron. Implementing this filter prior to the ceramic filter greatly extends the operation period between cleanings of the ceramic filter. The ceramic filter has a 0.9 micron rating of greater than 99.99% removal efficiency and a 0.5 micron rating of greater than 99.9% removal efficiency. Specifically, it provides comprehensive pathogen removal (Table 6).[96]

Table 6: Ceramic Filter Reduction in Bacteria/Cysts

Bacteria Removal	E. Coli	>99.99%
	Vibrio Cholerae (Cholera)	>99.99%
	Shigella	>99.999%
	Salmonella Typhi (Typhoid)	>99.999%
	Klebsiella Terrigenna	>99.999%
Cyst Removal	Cryptosporidium	>99.999%
	Giardia	>99.999%

Product Performance of ceramic filter proposed by the manufacturer.[96]

The ceramic filter addresses the stringent bacterial load requirements while still avoiding the use of chemicals. The ceramic filter is easy to maintain, as it can be periodically cleaned to improve flow rate, reduce pressure drop, and extend lifespan. The filter elements are brittle and susceptible to cracking and must be handled carefully. In the prototyping phase, one of the six ceramic candles was shattered after a valve upstream was opened, allowing water to flow back into the empty filter.

Granular Activated Carbon Filter

GAC is an imperative media filter for small-scale systems. GAC is found in many U.S. households in the form of a Brita filter; however, for the purpose of greywater filtration, there are additional benefits to including GAC filtration. Most importantly, GAC removes surfactants and other organic compounds, all of which were concerns in the filtration pathway. By incorporating a GAC filter, the team aimed to reduce most of the COD, TOC, and TN.

The largest available Pentek filter housing was chosen to increase the mean residence time of the system, one of the most important metrics for increasing the efficiency of the GAC filter.[69] In keeping with the desire for sustainable materials, a coconut shell-derived GAC media was selected, which also has some benefits for the purpose of water filtration, such as greater VOC absorption.[78,79]

Ultraviolet Filter

Because the rules of the 2017 Solar Decathlon competition prohibited chemical treatment of recycled water, UV disinfection was the default means of eliminating pathogens. To meet standards set by the National Water Research Institute, a dosage of at least 100 mJ/cm^2 needed to be delivered at all flow rates.[99] Few UV systems were available that could meet these standards. Of these, the team selected one (Viqua Model E4+) that was cost effective and provided a sensor to constantly evaluate that sufficient dosage was being met.

The UV system provides redundancy on the inactivation of microorganisms, which should be almost entirely removed upstream at the ceramic filter. This redundancy is critical because, from a practical perspective, one of the most important water quality parameters is the pathogenic load. During the Solar Decathlon competition, the only official water quality standard provided was the certainty that the water could not harm an animal after ingestion. The UV filter also inactivates viruses, which are small enough to make it through all filter elements within the system. The choice of UV disinfection over chemical inactivation methods was dictated by the Solar Decathlon, but it also plays into the design criteria that the team set. By implementing UV disinfection, the only operating input is electricity, which can be sourced from renewable energy. Conversely, the use of chlorine would inherently require nonrenewable operation and also introduce chlorine to the environment upon water use. Chlorination is also less effective than ultraviolet disinfection at penetrating and inactivating biofilms due to the rapid reaction rate of free chlorine.[100]

Synthesis of Non-Potable Water Standards

The testing methodology for the system aimed to verify if the effluent water met non-potable urban reuse standards. The EPA regulates potable water; however, there are no national standards for unrestricted non-potable urban reuse.[10,12] 32 states or territories have rules, regulations, or guidelines that address unrestricted non-potable urban reuse, and 40 states or territories have rules, regulations, or guidelines addressing restricted non-potable urban reuse.[93] Unrestricted reuse encompasses cases that allow public access to the released water, and restricted reuse implies some form of physical or institutional barrier to public access.

Unrestricted water regulations have more stringent standards than restricted water standards. For example, multiple states with unrestricted non-potable urban reuse standards require a minimum of secondary treatment and disinfection. Some states require even more rigorous levels of treatment.

The team chose to aim for unrestricted non-potable urban reuse standards because these standards are more pertinent to residential water use. To define non-potable water quality standards, the team synthesized various regulatory standards and literature recommendations. Table 7 is a synthesis of the most stringent standards for each water quality parameter in the states that regulate non-potable water quality. Any water quality parameter that is regulated by a state for non-potable urban reuse was included Table 7. However, the team elected to ignore mandated treatment pathways such as **secondary treatment** and coagulation, which were infeasible on the residential scale.

Table 7: Unrestricted Non-Potable Urban Reuse Standards

pH	Turbidity (NTU)	TSS (mg/L)	BOD_5 (mg/L)	TN (mg/L)	Total Coliforms (CFU/100 mL)
6.5-8.5	<2	<5	<10	<10	Average: <2.2 Maximum: <23

Synthesis of states unrestricted non-potable urban reuse standards based on the most stringent standards

The pH range of 6.5-8.5 was derived from the EPA's suggested secondary drinking water regulations.[19] A turbidity of less than 2 NTU is specified by several states.[92] TSS below 5 mg/L is specified by Florida, New Jersey, and North Carolina.[92] BOD below 10 mg/L is specified by North Carolina and Virginia.[92] TN regulation is less common, but New Jersey, Arizona, and North Carolina all specify some nitrogen-based guidelines. Arizona uses 10 mg/L as a cutoff for some special requirements, New Jersey requires less than 10 mg/L ammonia- and nitrate-based nitrogen, and North Carolina requires less than 4 mg/L monthly ammonia values.[92] To incorporate both ammonia and nitrate values, the New Jersey regulation was selected to represent the team's desired TN value. One of the most common regulations for fecal coliforms is a seven day median below 2.2 CFU/100 mL; however, a more stringent total coliforms seven day median cutoff of 2.2 CFU/100 mL is regulated by California, Nevada, and Washington.[92]

TOC is the only tested variable not specifically controlled in water quality testing. This is because TOC is typically only measured as an analysis for post-chemical treatment. Therefore, TOC removal is expressed as a percentage removal from the starting value, rather than a numerical threshold. The percentage removal value is based on the starting

TOC as well as the initial alkalinity (Table 8). All measured greywater TOC values were around 100 mg/L or higher, so the row corresponding to a TOC over 8 mg/L was used. Alkalinity was not explicitly measured, but it was estimated by converting pH values to alkalinity values (Table 9). Because pH was always within the range of 6.50-7.80, the "alkalinity of 0-60" column was used. Based on the starting parameters, 50% of the TOC needed to be removed for the sample to be considered successfully treated.

Table 8: TOC Removal Standards

Water	Raw Water Alkalinity (mg/L as $CaCO_3$)		
TOC (mg/L)	Less than 60	60 to 120	Over 120
2 to 4	35%	25%	15%
4 to 8	45%	35%	25%
Over 8	50%	40%	30%

TOC removal standards adapted from the Texas Commission on Environmental Quality.[101]

Table 9: Conversion of pH to alkalinity

pH	Alkalinity in ppm $CaCO_3$	pH	Alkalinity in ppm $CaCO_3$
6.5	3	7.3	20
6.6	4	7.4	25
6.7	5	7.5	31
6.8	6	7.6	38
6.9	8	7.7	50
7	10	7.8	60
7.1	12	7.9	80
7.2	15	8	100

Conversion of pH into an estimate of alkalinity based on experimental data. Table adapted from Leitritz.[102]

Testing Methodology

Once the system was fully assembled, the filters were replaced and the system was charged with municipal water. Testing occurred over a period of eight weeks: the first four weeks focused on testing municipal water and the final four weeks focused on testing synthetic greywater. The municipal water testing phase established baseline values for water cleanliness, identified which filters contributed to different contaminant reductions, and determined the best sampling practices. The greywater testing phase was designed to simulate the system's filtration of residential greywater and assess the capability of the system to successfully filter contaminants to non-potable urban reuse standards.

Municipal water was obtained from the tap located in room 1224 in A. James Clark Hall at the University of Maryland. Before testing, the water was pumped into a holding tank that was connected to the filtration system. Municipal water was run through the precharged system for about one and a half residence times prior to sample collection. Once the system was purged, a 500 mL sample was collected at the inlet and outlet of the system. Another two samples were collected at the outlet after one and two additional residence times, respectively. The samples were then stored for measurement the following day. These samples were run in parallel with untreated municipal samples from the same source in order to establish a control. This control was used to show that the system did not contaminate the water. Additional side experiments were conducted to isolate and observe the effects that the Next Sand and GAC filters had on water quality. Samples were taken before and after the filters and compared against untreated municipal water as a control.

Greywater testing was conducted in a similar manner, but after pumping municipal water into the storage tank, synthetic contaminants were added and stirred until the mixture became homogeneous. The synthetic formula consisted of lactic acid, bentonite, cellulose, sodium dodecyl sulfate, glycerol, sodium bicarbonate, and sodium sulfate as described by Hourlier et al.[81] The components, functions, and concentrations can be found in Table 3. Greywater quality changes as it ages, so, to maintain consistency, all greywater that was unused after testing was disposed of after 48 hours, and the tank was cleaned and emptied.

After the samples were collected, they were tested for pH, turbidity, COD, TOC, and TN. Testing for municipal and greywater samples included various biological, physical, and chemical compounds that could be observed. Turbidity was measured using a Hach 2100N turbidimeter. Calibration was done using a set of standards including turbidity values of 0.0, 20.0, 200.0, 1000.0, and 4000.0 NTU. A 20 mL sample was obtained from the original collection flask and vortexed. The sample was then inserted into the turbidimeter and measured immediately. Then, the sample was removed, the lid was closed, and absorbance reading was allowed to return to zero. This process was repeated twice for a total of three replicate measurements per sample.

Several chemical measurements were taken in addition to the physical measurements. These include pH, COD, TOC, and TN, which were used to assess whether the filtration system could sufficiently remove contaminants to reach the target non-potable urban reuse standards.

pH

The pH measurements were taken using a VMR Symphony B40PCID pH probe. The pH probe was calibrated using standard solutions at pH 4.00, 7.00, and 10.00. The sample collection bottle was shaken before inserting the pH probe directly into the source. Three replicate measurements were taken for each sample. Between measurements the pH probe was rinsed with deionized water and dried using Kimwipes.

Total Organic Carbon and Total Nitrogen

TOC and TN measurements were taken using the same equipment, the TOC-L Shimadzu Total Organic Carbon Analyzer with TNM. The large sampling container was shaken, then 40 mL of sample were poured into a sampling tube which had been pre-baked at 450℃ for two hours to sterilize and remove any moisture and residual organic matter from the cleaning process. In addition to one sampling tube for each sample, four standard solutions were created ranging from 0 to 10 mg/L nitrogen (0-17.17 mg/L carbon) taken in dilutions from a stock glycine solution at 1000 mg/L nitrogen (1715 mg/L carbon). These solutions were used to create standard calibration curves for nitrogen and carbon concentrations expected in the sample.

Chemical Oxygen Demand

Finally, COD measurements were run on the Hach DRB200 COD analyzer. Samples were collected from the larger sampling vial after shaking and added to solutions containing $K_2Cr_2O_7$. $K_2Cr_2O_7$ oxidizes chemically active species in the sample, and is itself reduced to Cr^{3+}. $K_2Cr_2O_7$ absorbs at 400 nm, while Cr^{3+} absorbs at 600 nm.[22] COD will almost always come out higher than BOD because BOD_5 does not account for chemical species that cannot be oxidized by biological processes. The ratio of BOD to COD for the synthetic greywater recipe that the team used was 0.14:1.[81] COD results are more reliable and reproducible than BOD_5 results.[103] BOD was not measured in the team's experiments because BOD_5 tests take much longer, and they detect fewer pollutants,. The mixture of $K_2Cr_2O_7$ and sample was incubated for two hours at 150℃ ± 2℃ and then measured with a spectrophotometer. Each sample was measured three times, and the replicate measurements were averaged to give the reported COD values. Samples were typically run once a week (similarly to TOC and TN) and stored in a 4℃ refrigerator until measured.

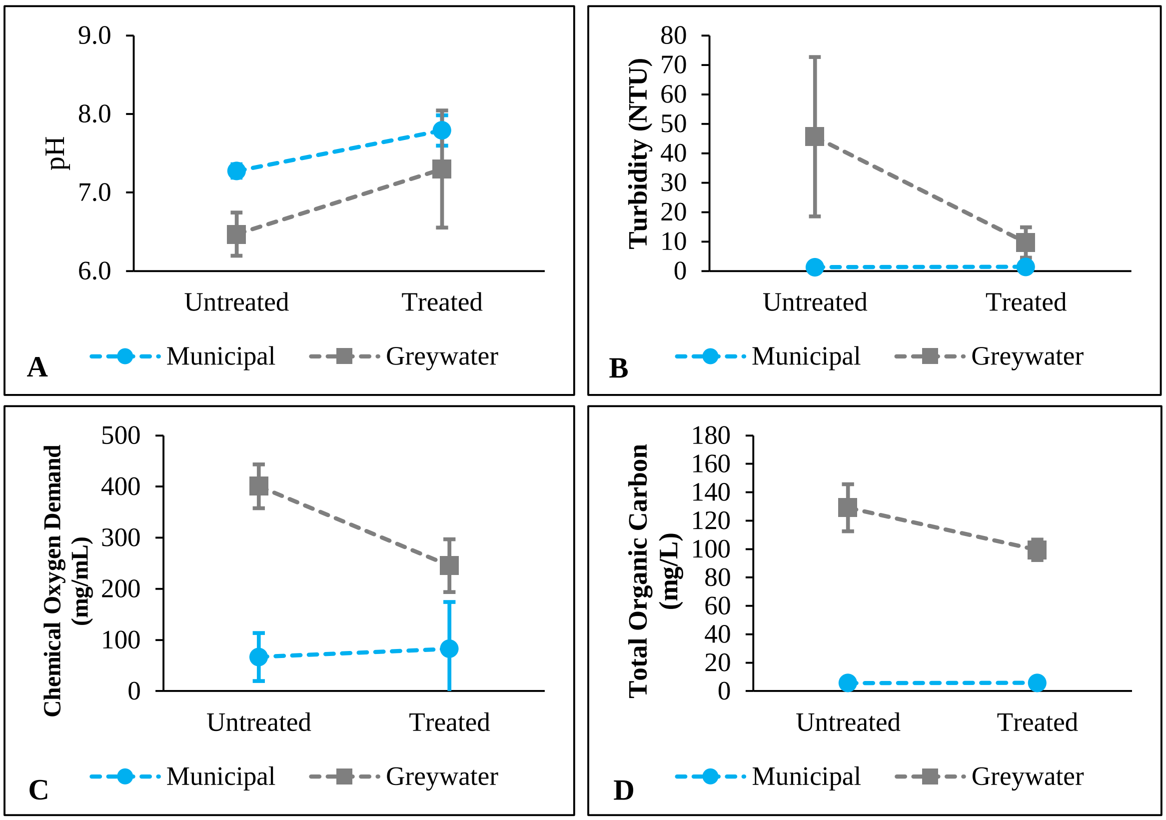
Statistical Analysis

Statistical testing for the data occurred in two steps, Analysis of Variance (ANOVA), and Tukey's Post-Hoc Analysis. ANOVA is used for comparing means across several groups. Typically, comparison of two groups is done using a t-test, which assesses the difference between the means in comparison to the pooled standard deviations divided by degrees of freedom. However, when multiple groups are analyzed together, the possibility of making an error, alpha, increases from 0.05 to $1 - 0.95^k$, where k is the number of t-tests combined to determine whether there is a difference across all of the groups.[104,105] For this experiment, in which four different test groups were used, the likelihood of making a mistake would be 0.185, more than three times higher than in a single t-test. ANOVA testing avoids the possibility of creating such errors. In the ANOVA test, the means of the sum of squares within and between treatments are compared. The mean of the sum of squares between treatments (MSB) is found by taking the difference between individual group means and the average of the group means, squaring and summing those values, and then dividing by the degrees of freedom. Mean of the sum of squares within treatments (MSW) is found by finding the difference between individual observations and the group mean, squaring those, adding them, and then dividing by degrees of freedom. The final statistic for the ANOVA test is the Fisher coefficient, found by dividing MSB by MSW. If this value falls above the critical Fisher coefficient value, then at least some of the groups tested are statistically significant from each other.[104,105] At a Fisher coefficient value over the critical threshold, $p < 0.05$, the likelihood of accepting a significant result by mistake is 5%.

In order to further determine which groups are statistically different from each other, a Tukey's Post-hoc test is used on each set of means. In a Tukey's test, the means for each group are compared against each other. The difference of the means is then divided by the standard error between the groups, found by dividing MSW in the ANOVA calculation by the number of samples in each group. If the number of samples in each group is different, the groups are averaged by taking the number of groups (k) and dividing by the sum of the reciprocals of the numbers in each group (i.e. 1/Na + 1/Nb). This is different than performing a t-test because the statistic using the squares within groups and the number of samples within groups takes into account the effects of all tested groups rather than just the two in the individual comparison being done.[106,107]

Chapter 4: Results

To determine the effectiveness of the filtration system, municipal water and greywater were analyzed across several parameters both prior to and following treatment. The mean and standard deviation values for each parameter were determined and analyzed with ANOVA and Tukey's Post Hoc Analysis.



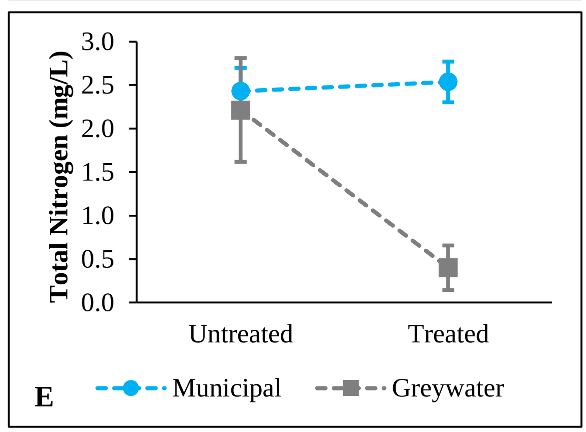


Figure 4: Values for treated and untreated municipal and greywater samples across measured parameters. From top left to bottom right: pH (A), turbidity (B), COD (C), TOC (D), TN (E). For municipal data, n = 19, where n is the number of samples. For greywater samples, n = 10.

Water quality was assessed by measuring pH, turbidity, COD, TOC, and TN for each sample collected. Prior to treatment by the filtration system, the average pH of the source municipal water was 7.27 ± 0.09 (Figure 4A). After treatment, the pH rose to 7.79 ± 0.19. The pH of the synthetic greywater was more acidic, with a pH value of 6.47 ± 0.27. After running greywater through the system, the pH increased to 7.30 ± 0.75, which was similar to the pH of untreated municipal water.

Before and after treatment by the filtration system, the average turbidity of the municipal water was 1.3 ± 0.5 and 1.4 ± 0.8 NTU, respectively, with the average values differing by 0.1 NTU (Figure 4B). The turbidity of untreated synthetic greywater was 45.6 ± 27.1 NTU, which was highly variable. After treatment, the turbidity was reduced to 9.7 ± 5.2 NTU.

Untreated and treated municipal water had average COD values of 67 ± 47 and 83 ± 91 mg/L, respectively (Figure 4C). Untreated and treated synthetic greywater had COD values of 401 ± 43 and 245 ± 52 mg/L, respectively. The filtration system moderately reduced COD for greywater but not to the levels observed in municipal water. The system also increased the COD of relatively clean tap water. The COD values were highly variable, even for untreated municipal water, which calls into question the validity of the data.

The average TOC values for untreated and treated municipal water were 5.7 ± 2.0 and 5.7 ± 1.6 mg/L, respectively, with a difference in average TOC of only 0.025 mg/L (Figure 4D). The TOC values for greywater were much higher, measuring 129.1 ± 16.5 mg/L prior to filtration and 99.4 ± 7.2 mg/L after.

The average TN values for untreated and treated municipal water were 2.430 ± 0.268 and 2.537 ± 0.234 mg/L, respectively (Figure 4E). The TN values for both untreated and treated greywater were lower than their municipal counterparts. Untreated greywater was more variable, with TN values of 2.215 ± 0.596 mg/L. Unlike treated municipal water, treated greywater showed significant reduction to TN levels of 0.401 ± 0.255 mg/L.

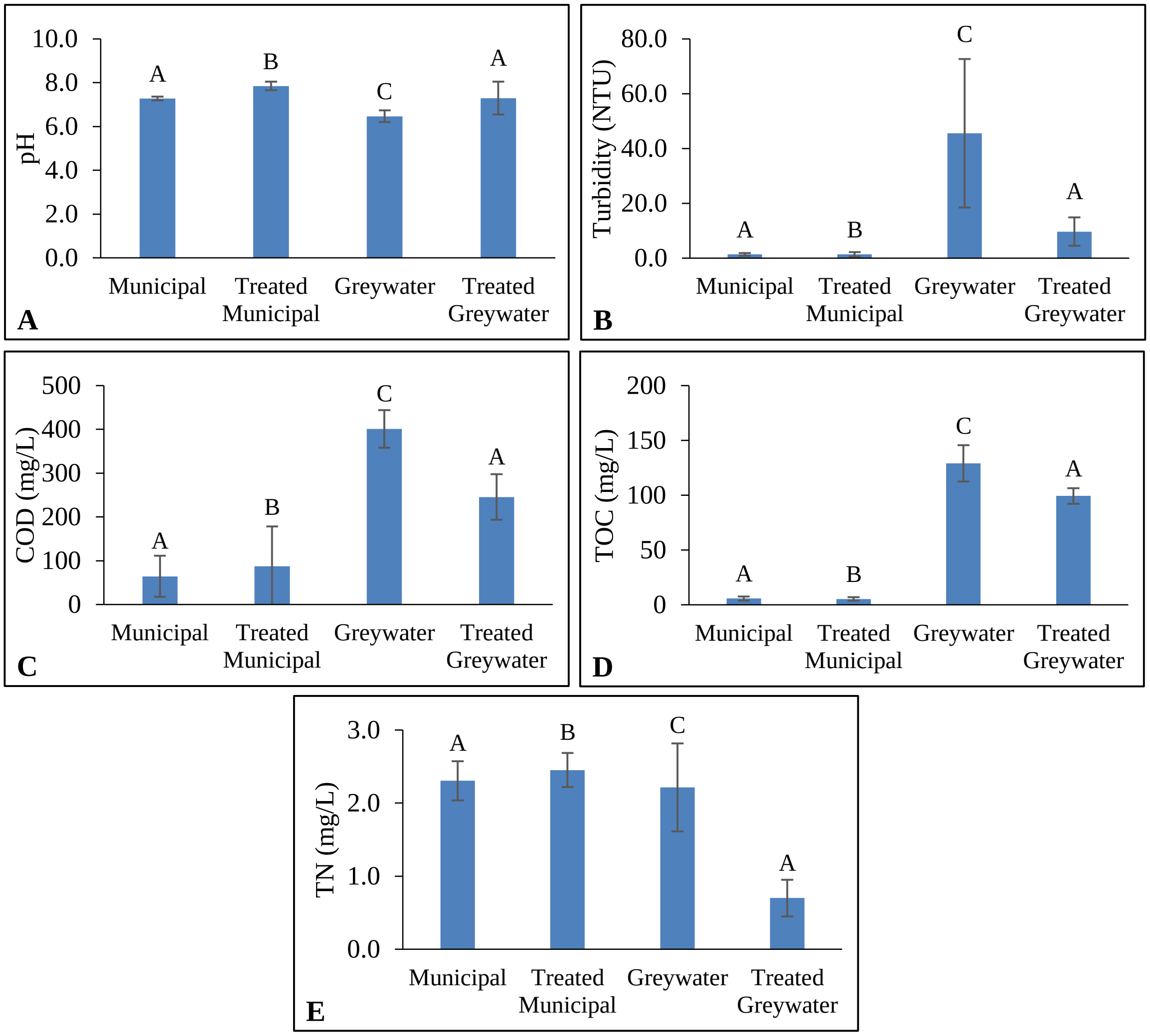


Figure 5: Analysis of Variance and Tukey's Post Hoc Analysis were performed across all four treatment groups (treated and untreated greywater and municipal water). The letters above the graph indicate which groups have statistically similar means. From top left to bottom right, pH (A), turbidity (B), COD (C), TOC (D), TN (E).

Analysis of Variance (ANOVA) was performed for all measured values for the treated municipal, treated greywater, municipal, and greywater samples, followed by Tukey's Post-Hoc Analysis to determine which of the treatment groups were significantly different from the others. For pH, across all four groups, there was statistically significant variation in sample means F(3,51) = 30.09, p = 2.44e-11. Municipal and treated greywater had similar pH values, while treated municipal water had a higher pH than municipal and treated greywater, and greywater had a lower pH (Figure 5A). Turbidity also had statistically significant differences across the four treatments F(3,51) = 37.78, p = 5.34e-13 (Figure 5B). Values measured for untreated and treated municipal waters as well as treated greywater were similar, while those for untreated greywater were statistically significantly different. Similar patterns were seen across COD and TOC measurements (Figures 5C-5D). Both tests resulted in statistically significant differences across all four groups. For COD, F(3,51) = 71.53, p = 2.78e-18. For TOC, F(3,51) = 869.28, p = 9.36e-44. For both tests, untreated greywater had the highest mean, which was significantly different from treated greywater. Both of these values were also significantly different from the values seen for treated and untreated municipal water. TN values displayed a pattern not seen in any of the previous tests performed (Figure 5E). There was a statistically significant difference between the four treatment groups of F(3,51) = 16.53, p = 1.25e-7. However, upon analysis using Tukey's Post-Hoc Analysis, it was determined that three of the treatment groups were actually similar to each other. Treated municipal water, untreated municipal water, and untreated greywater had similar means, while treated greywater had a significantly lower mean.

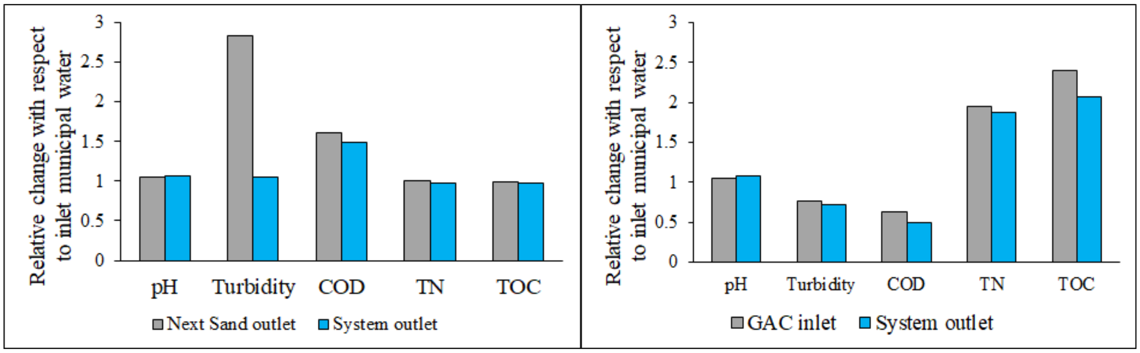


Figure 6: Changes in water quality relative to municipal source water. Left: values measured before and after the Next Sand filter. Right: values measured before and after the GAC filter.

To better isolate individual filtration methods, samples were taken from various locations in the system. All of the data were collected from runs using municipal water. Figure 6 shows the results of samples taken from the source water, the end of the system, and directly after the Next Sand filter. The filters up to and including the Next Sand ostensibly added both turbidity and COD to the source water (Figure 6). Although the relative change in turbidity appears significant, the absolute value change was below 3 NTU. The increase in turbidity was easily mitigated by downstream filtration; however, the change in COD saw only moderate attenuation.

Another filter element of interest for isolation was the GAC media filter. In this case, the samples were taken immediately prior to the GAC filter and after the UV. This essentially isolated the GAC because the UV only affects pathogenic load. As such, the observations from this experiment were entirely attributable to the GAC filter. The GAC clearly assisted in improving the water quality with regards to the COD and TOC, with smaller improvements in the turbidity and the TN loads. Although not obvious due to the scale of the vertical axis, the pH was also moderately adjusted by the GAC, which shifted the water to be more alkaline.

Chapter 5: Discussion

Discussion of Experimental Results

The goal for this system was to filter synthetic greywater to unrestricted non-potable urban reuse standards. These standards are an amalgamation of the most stringent standards set by U.S. states that have regulations or guidelines for unrestricted non-potable urban reuse (Table 7). The EPA does not publish national standards for any form of non-potable water recycling. College Park, MD municipal water likely fails the BOD standards for non-potable water depending on the true ratio of BOD/COD. This speaks to both the difficulty of achieving these standards and the relatively poor quality of municipal water in the local area.

pH

The pH values increased after treatment for both municipal water and synthetic greywater (Figure 4A, 5A). These results are within the range of expected values and, for all treated water samples, meet the EPA recommendations for drinking water (6.5-8.5).[19] The increase in pH after filtration can be attributed to the Next Sand and the GAC filters. With the GAC media, pH changes are not surprising, as the media is capable of CO_2 adsorption, which increases the pH of the water.[108,109] The Next Sand may be acting in a similar manner to the GAC, but there is no literature specifically on the sorptive properties of Next Sand material.

Although difficult to observe due to the scale of the axes, the data represented in Figure 6 demonstrate that the pH of municipal water increased following treatment by the GAC and by the Next Sand filter in the isolation experiments. In the case of the samples taken at the Next Sand outlet, the data suggests that 97% of the change in pH is attributable to the Next Sand filter, with an initial pH of 7.30, a final pH of 7.73, and a reading of 7.72 after the Next Sand. Although the pump and the 74 micron spin-down filter could have technically contributed to the observed pH change, their contribution is expected to have been inconsequential. In the case of samples taken directly prior to the GAC, the data suggests that 43% of the pH change is attributable solely to the GAC media, with an initial pH of 7.24, a pH of 7.57 prior to the GAC, and a pH of 7.82 after the GAC and UV. These two data points appear to conflict, with one experiment showing nearly all pH changes coming from the Next Sand and the other showing about half coming from the GAC.

The synthetic greywater is moderately acidic relative to the municipal water from which it was synthesized. Among all greywater samples, the average pH was 6.47, and the average municipal pH was 7.27. The filtration system noticeably increased the pH for both sets of water samples, with an average overall increase in pH of 0.63. This increase was imperative in shifting the greywater samples into the potable water range of 6.50 to 8.50, which is identical to the non-potable standard for this project.

Turbidity

Untreated and treated municipal water both had very low turbidity values, which were well within the acceptable range. The turbidity of untreated synthetic greywater was highly variable, ranging from 19.4 to 87.9 NTU. The composition of real greywater is highly variable based on household and location, so the variation in turbidity values of the synthetic greywater is acceptable. Treated synthetic greywater was less variable with a standard deviation of 5.2 NTU and a decrease in mean turbidity of 35.9 NTU, although the decrease in variability may be attributed to the lower mean. While this reduction was consistent across variabilities of source water, the treated water still had turbidity levels above the non-potable water standard of 2.0 NTU (Figure 4B, 5B).

The team isolated the Next Sand filter and measured the turbidity of municipal water entering and exiting the filter and found that the turbidity of the outlet water was nearly three times the turbidity of the inlet water. This large relative change was because the untreated municipal water was initially clear (with a turbidity of 1.1 NTU) and had an absolute increase in turbidity of only 2.1 NTU. The team also measured the turbidity of the municipal water exiting the entire system and found that it decreased back to the inlet value (Figure 6). These results suggest that the Next Sand filter may have been leaching some of its mineral media into the water, which was consequently removed by the 1 micron and ceramic filters. It is possible that this source of extra contamination caused the 1 micron filter and ceramic filter to foul more quickly, reducing the flow rates and increasing the pressure loss.

Chemical Oxygen Demand

There was a sizeable degree of variation among all of the COD testing results, even for clean municipal water, suggesting potential issues with sample preparation or the equipment itself. To test this, the COD value of a single sample of water was measured four consecutive times, with values of 47, 96, 79, and 93 mg/L. This confirmed that the COD measurements were inconsistent. Because of this, it is difficult to draw strong conclusions about the COD data. However, even with the high variability, there was still a substantial reduction in COD before and after treating the synthetic greywater, decreasing from an average of 401 to 245 mg/L (Figure 4C, 5C).

Because of the difficulty in measuring BOD_5 and the large variance associated with it, the team opted for the measurement of COD, which is inherently greater than or equal to BOD. Raw wastewater typically exhibits BOD/COD ratios on the order of 0.5:1, while treated water can have ratios near 0.1:1.[23,81]

To compare COD and BOD values within the greywater samples, literature data will be used to fill the gap in BOD_5 sampling capability. The literature on greywater synthesis reported a BOD/COD ratio of 0.14:1.[81] Considering the similarity between literature greywater properties and this system's greywater formulation, this BOD/COD ratio will be assumed identical for the considerations relative to the BOD regulatory standard.

Unfortunately, the calculated BOD equivalent of the average COD values for the treated greywater was still higher than the team's target limit. The measured COD value of 245 mg/L converted to a BOD equivalent of 34 mg/L, which exceeded the limit of 10 mg/L.

The Next Sand and GAC isolation experiments suggested that COD increased after being filtered through the Next Sand filter and decreased following the GAC filter. One possible explanation for this is that the Next Sand filter or other components prior to the Next Sand filter leached contaminants into the water stream (Figure 6).

Total Organic Carbon

The TOC levels for municipal water before and after treatment were low. This is to be expected as any increase in TOC levels would mean that the system added unwanted organic carbon to the water. During greywater testing, TOC levels were reduced on average by 23% relative to the pre-treatment samples. The filtration system was consistent in this reduction, albeit small in magnitude (Figure 4D, 5D).

The Next Sand isolation experiment showed minimal change in TOC after the Next Sand filter. On average, the TOC concentrations for untreated and treated municipal water were nearly identical, indicating that the filtration system may be unable to effectively reduce TOC when it is below a lower limit. However, the results of the GAC isolation experiment suggest that there was carbon introduced to the system before the GAC inlet; the TOC value at the GAC inlet was greater than double the TOC value of the source water. The data suggest that the GAC was able to reduce the TOC value back to double the inlet municipal water (Figure 6). This seemingly contradicts the TOC results for other experiments, because, in this specific case, the outlet TOC value was twice the inlet TOC value. Because the source was clean municipal water, the observed increase in TOC was very small in absolute terms; it increased from 2.4 mg/L to 4.9 mg/L. This change may have been due to leaching of the Next Sand media.

Total Nitrogen

The average TN values for untreated and treated municipal water were very similar, differing only by 0.107 mg/L. Untreated greywater had slightly lower TN values than municipal water. Treated greywater showed a moderate reduction in TN, from 2.215 to 0.401 mg/L. This difference is surprising, considering the insignificant change in TN from untreated to treated municipal water. It is possible that the introduction of certain contaminants, like surfactants, actually caused the nitrogen-containing compounds to be removed by adhering to other contaminants, which were then removed as expected. The treated greywater water met the target range for non-potable reuse (Figure 4E, 5E).

The isolation experiments showed no significant change in TN before and after the Next Sand filter, suggesting that the Next Sand media did not play a role in the removal of nitrogen-containing compounds. The GAC isolation experiment showed a two-fold increase in TN levels before the GAC inlet compared to the source municipal water. The TN levels did not significantly change at the GAC outlet. However, this means that the TN value at the outlet of the system was almost double that of the inlet. While in absolute terms this change is small, this result seemingly contradicts with the rest of the data on average, as the TN values remained similar for the rest of the municipal samples (Figure 6).

Discussion of system design

While testing the system and working with it on a frequent basis, many of its faults and shortcomings became apparent. There is room for improvement within both the chosen hardware as well as the design itself. The hardware improvements range from eliminating the presence of PVC to the incorporation of additional filtration elements. One operational shortcoming of the system is the drop in outlet pressure and flow rate over time as the system is run. As the membranes foul due to continued use, the pressure drop across the elements increases, which consequently reduces the system outlet to a trickle over the course of a few hundred liters of water. One simple solution to this issue would be a more powerful pump. Alternatively, an additional pump could be integrated to the system on the downstream side of the ceramic filter because most of the pressure drop in the system occurs across this filter. For integration with reACT, a more powerful pump would be difficult to implement, as no 240 V circuits are available in the mechanical room. A second pump would also prove troublesome, as the number of 120 V outlets is limited. Either improvement would require a significant rework of the electrical system.

Another hardware addition that could improve the operation of the system would be a floating intake for the greywater storage tank. Because the storage tank can function similarly to a settling tank, it would work to pull water from the top of the tank to avoid potential intake of settled solids. The current design falls short in this regard, as it pulls water from near the bottom of the tank. For the laboratory purposes, this did not prove troublesome because synthetic greywater shows minimal settling. However, in practice, the system should implement a floating intake, as solids will settle in real greywater.

The system proved poor in reducing COD of the synthetic greywater. Although GAC is very effective at combating COD over long time scales, at the relatively low mean residence time of the system, GAC is only able to moderately reduce COD. To improve this, hardware changes are necessitated. Either additional or larger GAC filters must be implemented within the system to increase the overall contact time, or new filters must be added. Trickling filters can remove upwards of 80% of COD and coagulation can remove upwards of 60% of COD.[42,50] Although coagulation is not feasible on this small scale, a trickling filter may be viable. Nevertheless, additional GAC requires the least maintenance and is the most proven of these technologies on a residential scale.

With regards to water filtration in reACT, the major design change that should be considered is the separation of rainwater and greywater into different filtration systems. Rainwater should be treated separately to produce potable water, which could supply any household purpose. This differentiation between water sources would vastly improve the water budget of the house by introducing a potable source, while also allowing the rainwater to be downcycled to greywater for irrigation. This could enable a true net-zero water budget in the scenario that more rainwater can be harvested than the amount of potable water consumed.

Overall, the system generally functioned as expected, but it fell short on certain metrics of importance. The turbidity and the COD of treated greywater were higher than desired. Further reduction of turbidity is nontrivial, because the ceramic filter is already nominally catching all particulates greater than 500 nm in size. Incorporation of ultrafiltration or nanofiltration would improve the turbidity reduction at the cost of a much greater pressure drop. Considering the pump has already reached its pressurization limits with the existing filters, the incorporation of additional filters that are even more taxing would likely incapacitate the system. Taken together, the many considerations and outstanding challenges of the treatment of greywater on a residential scale demonstrate the intractable nature of the problem.

Based on these results, the team recommends that a community-scale version of greywater filtration be considered. Pulling from this project, a pilot-scale plant capable of successfully reaching the required standards is a more viable real-world system. It removes much of the economic infeasibility observed on a single-household scale, and allows for more intensive purification techniques such as coagulation and trickling filters. Isolation studies have suggested that the Next Sand filter may be a potential source of leaching. Rapid sand filters can replace the Next Sand filter and can include process intensification by incorporating GAC with the sand media. A community of this type would necessitate dual plumbing for blackwater and greywater, so it would only be viable for new developments. Additionally, on the residential scale, rainwater can be collected for initial potable demand, with greywater supply from the central community plant.

Maintenance Schedule

To maintain peak system operation, the system components must be properly cleaned. The Rusco spin-down filter should be purged when solids can be seen accumulating beneath the filter. The spin-down filters must also be washed by hand whenever the membrane surface has become visibly brown or black in color. The 1 micron bag filter can be washed by hand approximately once every other week. The ceramic filter fouled very quickly, on the order of hundreds of liters of greywater. This filter element needs to be cleaned whenever the output flow rate drops below desired levels. Washing the filter instantly improves flow rate and decreases pressure drop. Lastly, the GAC filter media should be replaced whenever the carbon surfaces become saturated. Although this is difficult to measure because it is heavily dependant on the influent quality and flow rate, a possible proxy indicator for GAC efficacy could be pH increase per residence time, which may be integrated with in-line monitoring. In the team's practice, the GAC was replaced approximately once every two to three months.

Best Practices and Lessons Learned

In the design and testing of the greywater filtration system, the team overcame numerous challenges and learned many useful lessons. From these experiences, a set of best practices were developed to enhance system functionality and ease testing and maintenance. In terms of system functionality, the most significant lesson in hindsight was that the Next Sand filter may not only be ineffective, but might also have been contaminating the water rather than purifying it. This conclusion is ostensibly supported by the data from the isolation experiment; however, such a design decision merits further analysis. Another potential mistake was to incorporate too many filters prior to the pump. While solids filtration before a pump is necessary to prevent clogging or damaging of the pump, the result is large head loss before the pump. Because most pumps viable for household integration can only pull water from moderate depths, there is little room for upstream pressure loss. The team also recommends keeping the reservoir height above the inlet. During the time that the system was integrated with reACT, the upstream pressure losses were exacerbated by having to pull greywater from a depth of a couple meters. In addition, the team suggests the use of a floating intake filter for the reservoir to avoid the suction of solids from the greywater tank.

The team also uncovered several helpful practices for testing and maintenance. It is important to avoid leaving stagnant greywater within the filtration system. The composition of the greywater promotes large amounts of bacterial buildup on filters elements, requiring additional maintenance and a long period of flushing the system. When the system must remain idle for extended periods of time, all remaining greywater should be purged from the system. Removing filter elements may also be beneficial, allowing for easy maintenance upon return. The team also suggests plumbing the system with valves and unions before and after every filter, allowing for the isolation of any component and easy manipulation of the system. The team recommends the inclusion of pressure gauges throughout the system and a flow meter near the outlet. This would enable immediate pressure drop readings, allowing timely maintenance when systems have fouled. Another improvement for maintenance and system uptime would be the incorporation of parallel elements for the filters most prone to fouling. This would allow the operation of the system while one version of the element is being maintained. In the team's system, the ceramic filter fouled the quickest and reduced the flow rate substantially, which necessitated frequent cleaning at the cost of system downtime and reduced testing.

Future Research

Future research should include supplemental greywater data collection to reduce the variance of the existing data. Additionally, the isolation experiments should be reproduced using both municipal and greywater sources. To clarify the effects of GAC and Next Sand filters on pH, further testing must be run from the same pairs of valve locations, as well as intermediate locations. The use of intermediate locations will confirm which of the physical filtration techniques are contributing to the changes in pH and to what degree.

Future research could more thoroughly focus on the Next Sand filter during filtration of synthetic greywater to better understand the extent of leaching versus filtration. Additionally, isolation studies on the micron filters, ceramic filter, and UV filter should also be performed. Additional isolation studies would also provide insight on the inclusion of stepped micron filters versus a single, fine micron filter.

Additionally, because household greywater is guaranteed to contain bacterial contaminants, future research should include retroactively testing all samples that have been refrigerated, for bacterial load. Testing should also include the intentional introduction of bacterial contaminants into synthetic greywater to analyze the capability of the filtration system to inactivate microorganisms. Ideally, aliquots of blackwater should be incorporated into the synthetic greywater to most accurately mimic the microbiological characteristics of real greywater.

In addition to the isolation study extensions and the introduction of biological contamination testing, future testing should include new methods designed to better understand the cycling of nitrogen during the filtration pathway. As mentioned above, reduction in nitrogen loads in the treated greywater were not seen in treated municipal samples. To better understand this phenomena, the team proposes using a series of specific nitrogen tests in order to determine which components of total nitrogen are being reduced, and in what ratios they are found throughout various locations of the system. To measure dissolved nitrogen, the team recommends an alkaline persulfate oxidation method.[110] Nitrate and nitrites can be analyzed using cadmium-copper or cadmium-mercury columns.[111–113] Finally, ammonia and ammonium can be collected and separated using an annular denuder. Ammonia and volatile amines can be collected using gas washing.[114] The concentration of these amines can be calculated based on the ammonia concentration determined by experiments in the annular denuder. Proteins amino acids and other unmeasured compounds can be estimated based on the total nitrogen levels and the amount of unaccounted-for nitrogen left.

Lastly, the team proposes the addition of phosphorus testing. Phosphorus is generally present as phosphates in many nutritional sources, personal care products, and detergents.[115] While phosphorus is an essential element for most bodily systems, it becomes toxic at high levels and causes damage in those same systems.[116] Future testing of phosphate levels will reveal whether or not the system adequately lowers contaminant levels and whether the system needs an additional element to further address the issue.

Testing of iron and aluminum levels could be similarly revealing as they bind readily to phosphates and can affect detectable phosphorus levels.[117]

Future design iterations could incorporate the team's proposed changes, as well as expand upon the design beyond restrictions enforced by the Department of Energy's Solar Decathlon competition. It would also be worthwhile to perform an economic analysis on the system to compare it to existing small-scale filtration designs, giving a better idea of the feasibility to scale the system to a community level.

Chapter 6: Conclusion

Greywater filtration offers the possibility of conserving an invaluable resource. In a society and global climate moving towards water crisis, the advent of technology to reuse the salvageable fraction of household wastewater could prove critical. This system aims to advance current energy- and water-saving technologies on a residential scale. In the design, the team took into account the constraints of a conceptual house, the University of Maryland Solar Decathlon reACT house, for which the system was initially designed.

The team researched myriad filtration technologies focused on removing chemical, physical, and biological contaminants before settling on the five filters in the system: micron, Next Sand, ceramic, GAC, and ultraviolet. After constructing the house alongside the Solar Decathlon team, the team took the system out of the house for isolated testing, where the focus was turned towards quantifying pH, turbidity, COD, TOC, and TN. The team found that the system has the capacity to increase pH for both municipal and greywater samples post-treatment. All pH values fell within acceptable ranges for unrestricted urban non-potable reuse standards. Turbidity was low in both municipal and treated municipal samples. Municipal samples were also found to have comparable values to treated greywater, though greywater turbidity exceeded the limit for non-potable standards. Treated greywater showed improvements in COD and TOC, but failed to reach non-potable standards for either. TN was significantly lower in treated greywater than in any of the other samples.

The team isolated system components that may have contributed to the observed values. The Next Sand filter is believed to have slightly increased turbidity (less than 3

NTU), an effect which was outweighed by downstream compensation. Additionally, the GAC is believed to have significantly contributed to improving COD and TOC.

In the future, the team expects the system to be reinstalled in the Solar Decathlon reACT house so that it may serve as an active learning site and laboratory for the continued exploration of sustainable technologies. The team hopes to see the continuation of data collection on greywater filtration to non-potable and potable standards, as well as research into the potential application of this technology beyond reACT and into the future at the residential and community scales.

Glossary

Aerobic bacteria - bacteria that can survive and grow in oxygenated environment.

Anaerobic bacteria - bacteria that cannot live and grow in the presence of oxygen.

Biofilm - a thin, slimy film of bacteria that adheres to a wet surface.

Biosand filter - a filter which removes pathogens and suspended solids from water using biological and physical processes that take place in a sand column covered with a biofilm.

Blackwater - wastewater from toilets that cannot be practically reused or recycled.

Biological oxygen demand - measure of the amount of dissolved oxygen needed by biological organisms to metabolize organic matter in water.

Ceramic filters - a type of physical filter that utilizes the small pore size of ceramic material to trap contaminants.

Chemical oxygen demand - measure of the amount of oxygen that can be consumed in reactions in a given solution.

Chlorination - adding of chlorine or chlorine compounds to water.

Coagulation - process of a liquid changing to a semi-solid or solid state.

Colloids - homogeneous non-crystalline substance that contains large molecules or microscopic particles that do not settle, and cannot be removed via common filtration methods such as suspension.

Effluent - the out-flowing stream of water.

Electrical ballasts - device that limits the amount of current in an electrical circuit.

Electrocoagulation - type of coagulation of fluids that occurs when electric current is applied to produce concentrated heat.

First flush - the diversion of the first flow of water away from a rainwater catchment system.

Granular activated carbon filter - device consisting of bed of heated or treated carbon that uses chemical adsorption to remove impurities and contaminants.

Greywater - Recyclable, clean wastewater from baths, sinks, washing machines, and other kitchen appliances.

Hard water - water that has deposited high mineral content, such as calcium and magnesium carbonate, that forms soap lather with difficulty and leaves solid salt deposits when being heated.

Improved drinking water - World Health Organization classification for sources that, by nature of their construction or through active intervention, are protected from outside contamination, particularly faecal matter.

Influent - the in-flowing stream of water.

Magnetic ballasts - a lighting equipment that regulates the voltage received by a fluorescent light so as to not damage its bulb.

Membrane cartridge filtration - a filtration system that uses sieving mechanism to remove particles from water running through its membranes with pore sizes of 1.0 microns and larger.

Microfiltration - a physical filtration process that separates microorganisms and suspended solids from the contaminated fluid by forcing it to pass through membranes with pore sizes usually between 0.1 - 10 microns.

Micron filter - a type of physical filter that removes a wide range of contaminants using a membrane.

Nanofiltration - process that desalinates hard water by rejecting valence ions, organic matter, and salts from passing through.

Natural organic matter - complex mixture of organic molecules found in water from plant or animal sources, which as a result make it vary significantly from source to source.

Next Sand - a sand or multimedia filtration device composed of high purity alumino-silicate that uses adsorption, catalytic and ion exchange, and molecular sieve properties to purify water.

Nominal filtration - filtration of the smallest possible particle size trapped by a filter.

Reverse osmosis - process of directing a solvent through a porous membrane against the natural osmosis direction by subjecting pressure higher than the osmotic pressure.

Secondary treatment - Secondary treatment process include activated sludge processes, trickling filters, and rotating biological contactors.

Sedimentation - the process of depositing particles in a fluid to the bed of the container they are held in thereby clearing the top region of the fluid from large degree.

Surfactants - compounds that lower the surface tension of liquids they are dissolved in.

Total coliforms - representation of the bacteria found in water supply.

Total nitrogen - a measure of the particulate and dissolved nitrogen including nitrogen derived protein substances, ammonia, reduced nitrogen, nitrates/nitrites and organic carbon.

Total organic carbon - a measure of the carbon found in organic compounds in a solution.

Total suspended solids - solids that can not pass through a 0.45-micron filter and remain suspended when dispersed in water.

Turbidity - the cloudiness or haziness or a liquid caused by particulate matter.

Ultrafiltration - filtration using a medium fine enough to retain colloidal particles, viruses, or large molecules.

Ultraviolet disinfection- disinfection technique using ultraviolet irradiation to inactivate biological agents.

Unrestricted non-potable urban reuse - a classification of water purity deemed safe for use in irrigation of outdoor areas, toilet flushing, air conditioning, fire protection, construction, and ornamental water features.

Volatile organic compounds - organic chemical compounds whose composition makes it possible for them to evaporate under normal indoor atmospheric conditions.

Zeolite - microporous substance containing aluminum and silicate.

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