Design of Water Filter for Third World Countries

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Abstract

The residents in third world countries battle against waterborne diseases every day. It is a luxury to have access to safe drinking water. However, it is extremely difficult to invest on a water filter with minimal annual income. A low cost water filter can serve as a subsidy such that every family can take advantage of this luxury. In this thesis, literature reviews on existing water filters have been completed and design of a dual level water filter with ceramic and activated carbon is developed. Water flow rate tests are carried out to optimize water filter design. Further, the filter effectiveness in diminishing various contaminates is analyzed by a licensed sampling laboratory. A manufacturing line to produce the dual water filters is proposed and the cost of manufacturing a unit is calculated to be $1.53 USD, which is an affordable price for people in third world countries. With a low cost water filter available, residents in the third world countries could enjoy having safe drinking water and improve quality of life.

Acknowledgements

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Work Distribution

It has been decided that a collective document will be submitted for this project. The lists below indicate the sections each member has contributed to in terms of research and writing. By signing below, we agree to share the same mark for this project.

Research & Responsibilities	Sections Written
Background information research	4.6 Filter Comparison
Water standards research	4.7 Choice of Water Filtration Method
Activated carbon manufacturing methods	4.8 Study of Brita Filters
Concept generation	5.0 Water Standards
Transport to Maxxam Analytics	6.1 Carbon Manufacturing Methods
Final design computer modelling	6.2 Ceramic Manufacturing Methods
Report composition and editing	7.0 Prototype
	9.0 Final Design

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Louis Chan

Research &Responsibilities	Sections Written
Reverse osmosis filter research	Acknowledgements
Slow sand filter research	4.3 Slow Sand Filters
Activated carbon filter research	4.4 Activated Carbon Filters
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Flow rate testing	8.0 Testing
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Marcus Chan

Research & Responsibilities	Sections Written
Ceramic filter research	Abstract
Ultraviolet water treatment research	1.0 Introduction
Ceramic manufacturing methods	2.0 Background
Prototype builds	3.0 Objective
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Jingwen Wang

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1.0 Introduction

Drinking water conditions have great impacts on people's everyday life, especially in third world countries where access to safe drinking water is very limited. Surface water often is the only source, thus water contaminations are hard to avoid. Unsafe drinking water causes diarrhoeal diseases. Statistics shows that these diseases cause ninety percent of all deaths of children under five years old in developing countries, where children's resistance to infections are low [1].

Although municipal water in developed countries already fall into the World Health Organization (WHO) safe drinking water standards, water filters are still commonly used to improve taste or to eliminate any undesired matters. Various types of filters have been designed to be more suitable in the third world countries, but the cost is still not satisfactory and many products are imported which further add to the cost.

The scope of this project is to study the existing water filtration methods, and use the knowledge to design a water filtration system. This water filtration system will focus on cutting down the cost while maintaining filter effectiveness. It is preferred to have manufacturing plants set up on site and filters can be distributed locally to reduce any unnecessary costs. By providing affordable water filters to third world countries will greatly improve people's quality of living, and reduce the risk of any waterborne diseases therefore saving lives.

2.0 Background

Most of the people in third world countries do not have easy access to clean drinking water. While safe drinking water is essential for living, lack of access has resulted in many water related diseases.

Water filters are already being used in some third world countries including products such as LifeStraw. LifeStraw is a portable water filter designed for personal use. One LifeStraw costs about $3 USD [2]. It can filter at least 700 litres of water, and removes 99% of bacteria and viruses [3]. LifeStraw Family filter has also been invented recently at a cost of $25 USD [4]. LifeStraw Family is as effective as the LifeStraw, and can be used by a family for up to 3 years assuming 20L/day water consumption [5]. Compared to the under $1000 USD per capita income [6] in many third world countries, spending $25 USD on a filter is considered expensive. Ceramic water filters are also commonly used in some developing Asian countries. These filters are inexpensive and easy to manufacture. They are effective at eliminating bacteria and sediments, but they do not remove chemical contaminants [7].

Since contaminated drinking water contributes to disease world-wide, the World Health Organization (WHO) had created a set of guidelines for drinking water quality to set an international standard. These guidelines are often used in water filter designs. Flow rate and capacity of water filters are also need to be considered when designing water filters. In the US, the Reference Daily Intake (RDI) of water from sources other than food intake is on an average of 2L per capita per day [8]. This amount may vary due to the different circumstances, such as gender, age, and climate. For the purpose of this project, 2L per capita per day is used.

3.0 Objective

The objective to this project is to design a low-cost and easily manufactured water filtration system for use in third world countries. This water filtration system will include a water filtering component, a lidded container to hold clean water and a valve for easy access of water. Manufacturing facility arrangement will also be examined and planned. The water filtration system is designed to provide safe drinking water for households of four to eight people. Target manufacturing cost is around $2 apiece. In order to achieve the low cost, use of simple technology and readily available materials are the prime consideration needed to insure production of the filters in the local area.

Existing water filters have been analyzed and compared to determine the best type on the basis of cost, material availability, and effectiveness. Filter dimensions are calculated base on amount of water consumption per household and flow rate of filter. Water samples are analyzed at a licensed laboratory to demonstrate the effectiveness of the filter design and a working prototype will be available by the end of the academic year.

4.0 Literature Review

To gain more insight knowledge on the existing water filtration systems, research was done on five most common types of home use water filters. These are UV water treatment, reverse osmosis filters, slow sand filters, activated carbon and ceramic filters. Different filter types were studied and comparisons were made on factors including price, functionality, manufacturing process, maintenance and effectiveness.

Based on the characteristics of these filtration methods and the objective of this project, ceramic and activated carbon were chosen to the media to be considered. A well known water filter brand Brita as well as a candle ceramic filter were purchased and taken apart to be studied further on their structure and functionalities.

4.1 Ultraviolet (UV) Water Treatment

UV treatment is a disinfection process that works by having water pass by a special light source. The light source emits ultraviolet waves which inactivates harmful microorganisms. UV rays alter the nucleic acid (DNA) of viruses, bacteria, molds, and parasites, so that they cannot reproduce and are considered inactive. The process does not add chemicals to water, but the inactivated microorganisms are also not removed from the water [9]. UV treatment is not intended to treat wastewater or water that is visually contaminated. Particles in water can block the UV rays and allow harmful particles to survive. Therefore, UV water treatment is usually combined with pre or post filtration device to produce safe, potable water. Also, to ensure the proper usage of UV treatment, water should be tested beforehand, since hardness, alkalinity and such properties of water can influence UV effectiveness [9].

For household applications, point-of-use UV system is used. The system is small, portable, and can be attached to a faucet or mounted under the sink. UV system consists of a UV light source, protective transparent housing for the bulb, power supply, water chamber, and filters for pre/post –treatment [9]. Figure 1 shows the basic components of a simple UV filter with a pre filter built onto it. A unit of UV system costs from $300 (self installed), to $1200 (with more features). Maintenance of the UV filter involves UV bulb replacement to ensure proper emission of ultraviolet waves. Annual replacement of filter/bulb costs up to $150 [9].

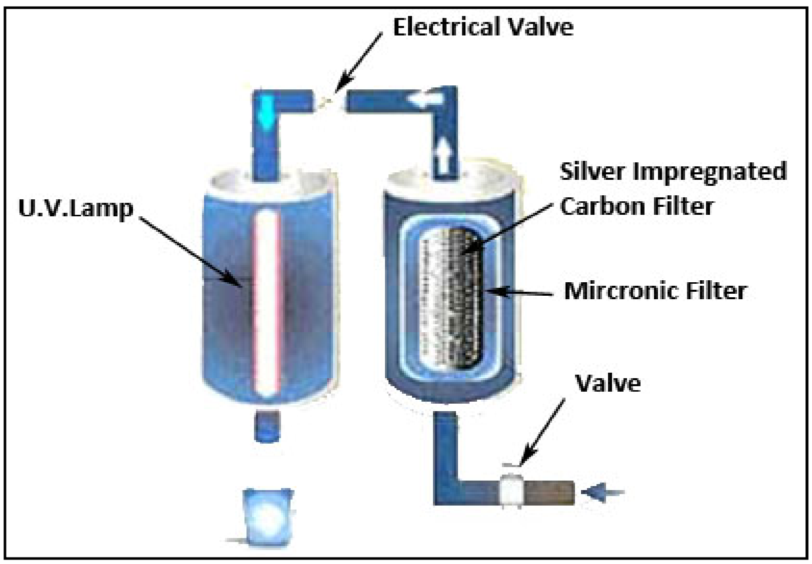

Figure 1 UV Water Treatment System [10]

4.2 Reverse Osmosis Filters

Reverse Osmosis water filters are typically used to improve drinking and cooking water quality in households. It is one of the finest water filtration methods and reduces almost all organic and inorganic chemicals, bacteria, microorganisms, salt, metals and particulates that are found in contaminated water [11]. It also improves tastes, odor and appearance. Reverse osmosis water filtration system includes a semi-permeable membrane and a booster pump [12].

These ultra fine membranes have pores of approximately 0.0005 microns in size [13]. Water is pressurized to about 40-45 psi and then forced through the membrane, removing anything that's larger than 0.001 microns. Pre and post filtrations are usually combined in a reverse osmosis filtration system. As for pre filters, a sediment filter is used to remove silt, sediment, sand, and clay particles that might clog the membrane. An activated carbon filter is also recommended, since minerals such as chlorine which will shorten the membrane's life. For post filtering, activated carbon filters are often used to further improve the smell and taste of water and to remove any leftover chemicals [14]. Figure 3 shows a reverse osmosis filtration system schematics with the most common components.

Reverse osmosis filtration systems come in various sizes and prices vary from $400 portable unit to $2500 stationary units where pressure system is installed. Pre filters need to be changed at least annually. As for the membrane, it may last for several years before a replacement need to be purchased at a price of $100 to $200 [12].

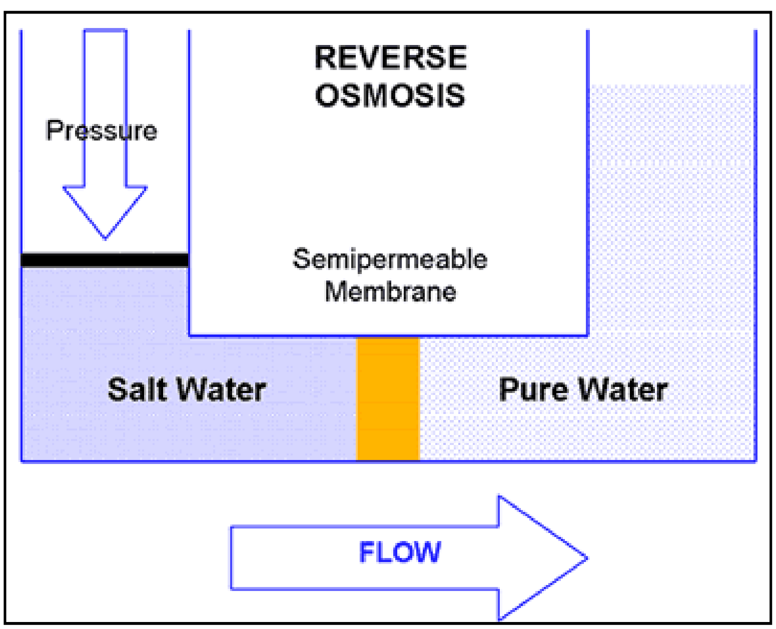

Figure 2 Reverse Osmosis Process [13]

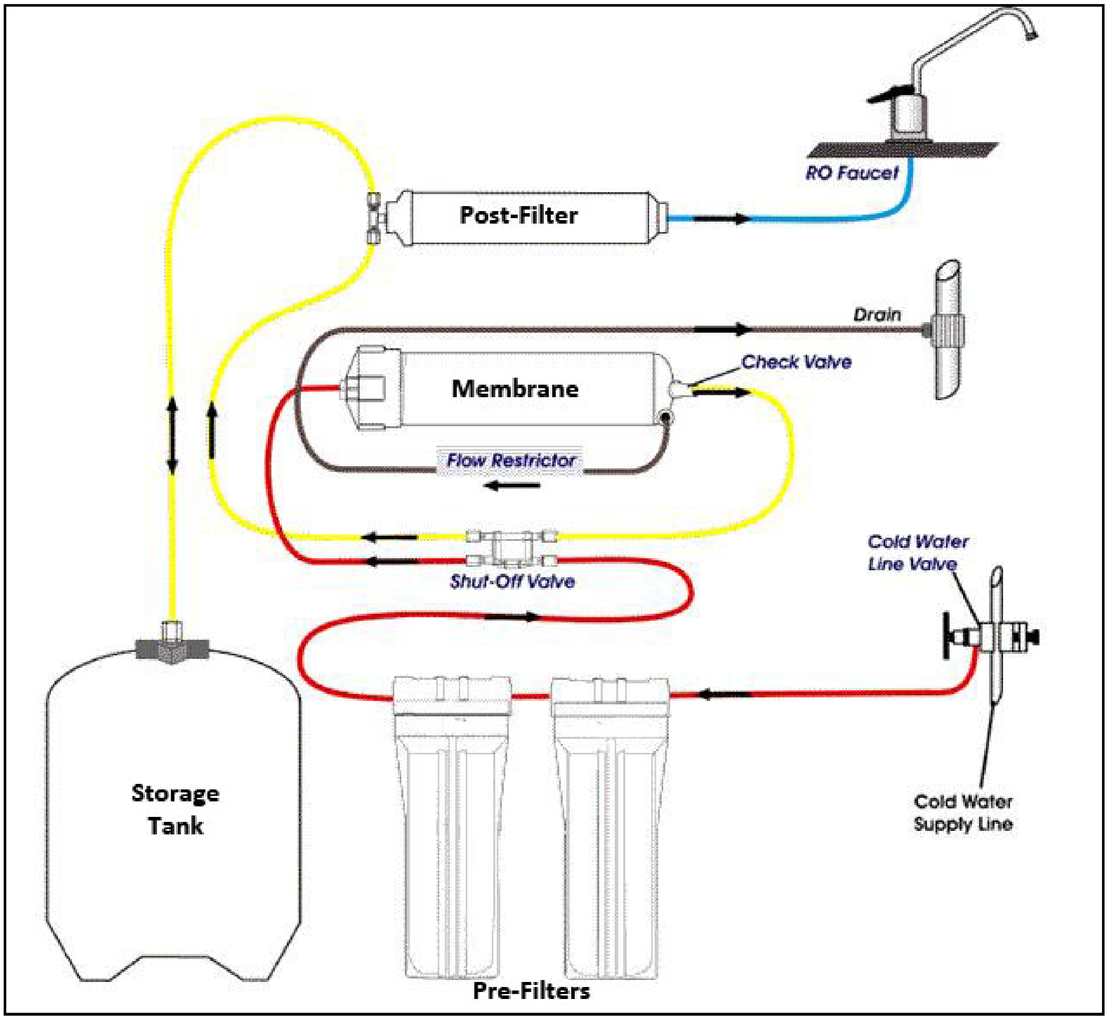

Figure 3 Reverse Osmosis Water Filtration System with Basic Components [15]

4.3 Slow Sand Filters

Unlike all the other water filtration methods, slow sand water filters utilize biological processes in a non-pressurized system to purify water. Slow sand filtration systems have already been used in many developing countries, and some developed countries such as UK also use slow sand filters to treat the water supply [16]. Slow sand filters are constructed with a bed of fine sand as the filtration media, and gravel to support the sand as shown in Figure 4. A complex biological layer, Schmutzdecke, which consists of bacteria culture, is grown on the surface of slow sand filter. As water passes through the Schmutzdecke layer, particles of foreign matter and dissolved organic material are adsorbed and metabolized. Slow sand filters can only filter water up to a certain turbidity level, since water with high turbidity clogs up the filter bed quickly. Slow sand filters are very effective at removing heavy metals, and it is often combined with activated carbon to remove organic material as well as to improve odor and taste [17]. Flow rate of slow sand filters are directly proportional to the dimension. It has a steady slow flow at an average of 250L/h/m^2, and the height of sand can be no less than 75cm for the filtration method to work properly [18].

The cost of making the filter oneself does not cost a lot of money, but for pre-made automated systems, it may cost $600 to $1000 depending on the size [19]. Slow sand filters can be easily maintained by backwashing the unit once every few weeks to wash way contaminates clogging up the surface. This insures a consistent flow rate.

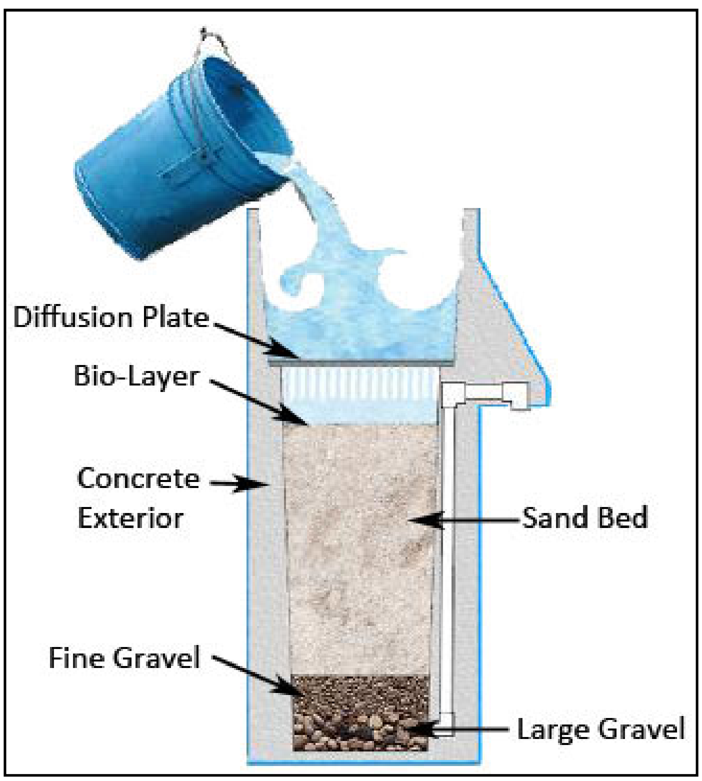

Figure 4 Bio Sand Filter Components [20]

4.4 Activated Carbon Filters

Carbon is known as a popular absorbent of impurities. Activated carbon is processed carbon with a slightly positive charge added to it and is more attractive to chemicals and impurities [21]. It is extremely-porous, thus provides high surface area to volume ratio which increases the rate of absorption [22]. Because of this property, activated carbon is commonly used in water treatment systems. Activated carbon can be used alone to improve tastes and odors, and it is most effective at removing organic compounds including VOCs, radon, and chlorine. It can also be used as pre-treatment for other water purification systems such as reverse osmosis and ultraviolet water filters [21].

Carbon can be obtained from a variety of sources such as coconut shell, wood or coal, and all of which are readily available practically everywhere in the world. The activation process is also quite simple and can be done with an industrial oven. Although carbon blocks have a higher contaminate removal ratio, granulated activated carbon are more commonly used in home filter systems. Activated carbon bits cannot be reused and need to be replaced after filtering about 150L of water [23]. Activated carbon has already been widely used, such as in Brita filters. Brita filter units cost about $7 USD in North America. A detailed study on Brita water filter element was carried out and presented in *Section 4.8*.

4.5 Ceramic Filters

Ceramic filter is one of the most economical filtration methods and it is already being widely used in some third world countries. Ceramic filter blocks anything larger than a water molecule, allowing only water to pass through the pores. When ceramic water filters are treated with colloidal silver, it can further prevent bacteria and the growth of mold and algae in the body of the filter [7]. Two styles of ceramic filters exist on the current market, pot and candle ceramic filters. Figure 5 shows a purchased candle ceramic filter. It consists of filter housing and a threaded plastic connection to water source. The filter is later dissected and studied further. Candle ceramic filters are sometimes filled with activated carbon to increase water purity. Flow rate of ceramic water filters are controlled by surface area and the amount of additives. For a pot filter with the ideal proportion mixture of filter material, flow rates of 1-3 L/hr can be achieved [24].

Ceramic filters are made with clay and combustible additives, all materials are inexpensive and can be easily found. Ceramic filters are brittle and high maintenance in comparison with other filters. Since sediments fill up the pores on the filter surface, they need to be cleaned regularly. To clean ceramic filters, scrubbing the surface with a brush or reverse-flow would be effective [25].

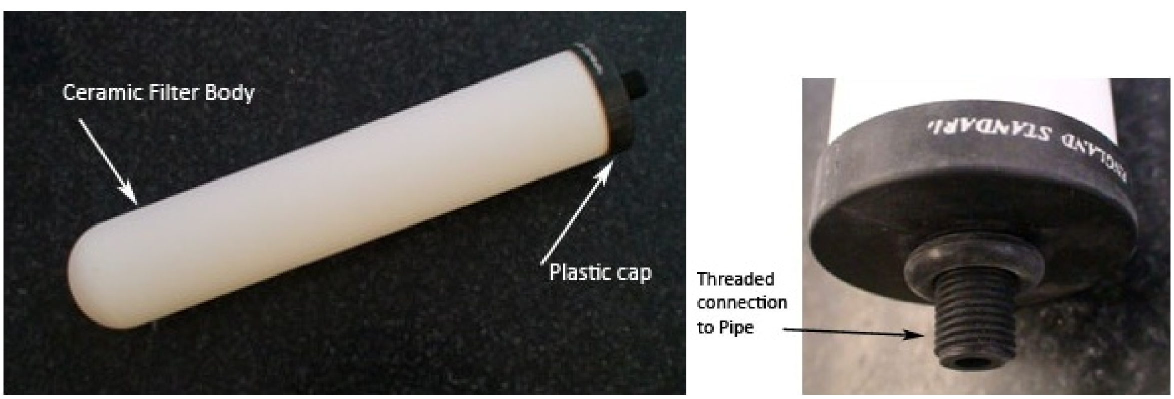

Figure 5 Ceramic Candle Filter

4.6 Filter Comparison

Tables 1 and 2 summarize the advantages and disadvantages for using each of the described water filtration methods.

Table 1 Contaminates Filtered by Various Water Filters [26]

	Arsenic	Bacteria and Viruses	Bad Tastes & Odors	Chlorine	Fluoride	Hydrogen Sulphide	Heavy Metals	Nitrates	Radon	Sediment	Iron	VOC's
Ultraviolet	○	●	○	○	○	○	○	○	○	○	○	○
Reverse Osmosis**	●	●	●	●	●	◐	●	●	○	●	●	◐
Slow Sand	◐	●	◐	○	○	○	●	○	○	●	●	◐
Activated Carbon	○	○	●	●	○	◐*	◐	○	●	●	○	●
Ceramic	○	●	◐	○	○	○	○	○	○	●	○	○

● = Effectively Removes ◐ = Significantly Reduces ○ = Minimal or No Removal

* At high contaminant levels, filter life will be reduced significantly. Manganese greensand (whole house iron reduction filter) or KDF filter is recommended for Hydrogen sulphide.
** Even though reverse osmosis is effective in removing bacteria and viruses, it is not recommended that you rely upon reverse osmosis solely if your water is contaminated with bacteria or viruses. Ultraviolet (UV) purification is also recommended.

Table 2 Advantages and Disadvantages of Various Water Filters

Filter Type	Advantages	Disadvantages
Ultraviolet	Inactivates bacteria	Requires electrical power Should not be used alone since it only inactivates bacteria Expensive
Reverse Osmosis	Filters most contaminates out of all other filter types	Expensive to make Need pressure to work system Requires pre filtering
Slow Sand	Cheap and easy to make Does not need electrical power or chemicals Material easily obtained	Large in volume Heavy Slow filtration rate
Activated Carbon	Cheap to make Material readily available Usually used as pre filter for other filtration systems	Does not remove bacteria Not very good at removing heavy metal
Ceramic	Cheap and easy to make Can be combined with activated carbon No advanced technology required	High maintenance, need to be cleaned periodically

4.7 Choice of Water Filtration Method

The main source of water in third world countries is surface water from rivers and ponds. Surface water contaminants typically consist of sediments, bacteria, viruses, VOCs and heavy metals. Bacteria and viruses are the main causes of waterborne diseases [27]. Therefore, eliminating bacteria and viruses would be the main task for the filter. Sediment and other solid particles also need to be removed to make the water drinkable.

Of the five filters studied, it is clear that all filters, except activated carbon, would eliminate bacteria and viruses. Ultraviolet treatment is perhaps the best method to inactivate bacteria and viruses, but not very effective on other contaminates. Ultraviolet treatment is also expensive. Reverse osmosis filters eliminate most contaminates, but since the target consumers are in third world countries, having low-cost manufacturing methods and readily available is critical. Reverse osmosis filters require technology not yet available in third world countries, and manufacturing cost is relatively high. Thus it is not suitable for this application. Slow sand filters are economical and material is also easily obtained. However, it only operates properly in large size. This is not viable for a typical home use water filter.

As shown in Table 1, the combination of activated carbon and ceramic filters would filter out most bacteria, viruses, sediments, VOCs, most heavy metals, chlorine, radon, and reduce odor and bad tastes in water. Activated carbon can be obtained from burning coconut shells and the processing of ceramic pots is also simple. The combination of activated carbon and ceramic filter compensates each other to provide the most effective filtering media. Thus, they were chosen to be the focus of the project.

4.8 Study of Brita Filters

Brita is a German company that specializes in water filtration products. Over the years Brita has became a leading portable home water filtration brand. To further study the components in a portable Brita home filtration product, a filter element was dissected. The physical make up of filter is very simple – filtration material enclosed inside a plastic casing.

Figure 6 shows the replacement filter is cut open from the plastic mesh part on the upper half of the filter. The filtration materials are made up of black and white particles, which are silver impregnated activated carbon and ion exchange resin respectively, seen in Figure 7.

Figure 6 Brita Filter Container

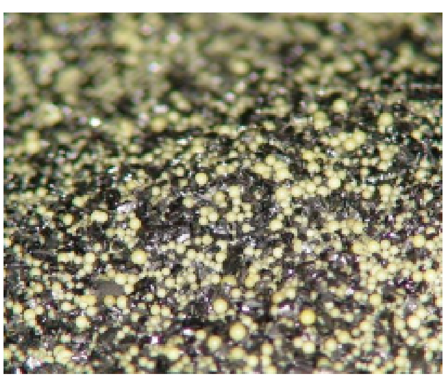

Figure 7 Activated Carbon and Ion Exchanger Resin

Slots on top of the filtration housing (Figure 8) allow water to flow into the filter element. Four openings covered in fine metal meshes on the bottom of the filter (Figure 9) allow water to pass through into the jug. The ion-exchange resin beads in the filter act like magnets and eliminate lead while reducing mercury, copper, cadmium, and zinc. It also absorbs calcium and magnesium to reduce water hardness. Ion-exchange resin beads are made from an organic polymer substrate with highly porous surface for exchange of ions [28]. In water filtration process, ion-exchange resin beads replace poisonous and heavy metal with sodium and potassium. The resin cannot be recharged and must be discarded at the end of life [28].

According to Brita, activated carbon that is made out of coconut shells, has extremely high micro porosity, allows fast adsorption and chemical reaction. The activated carbon used in Brita filters is treated with silver solution to prevent bacteria growth in the filter and kill bacteria in the water [29].

Figure 8 Filter Cover

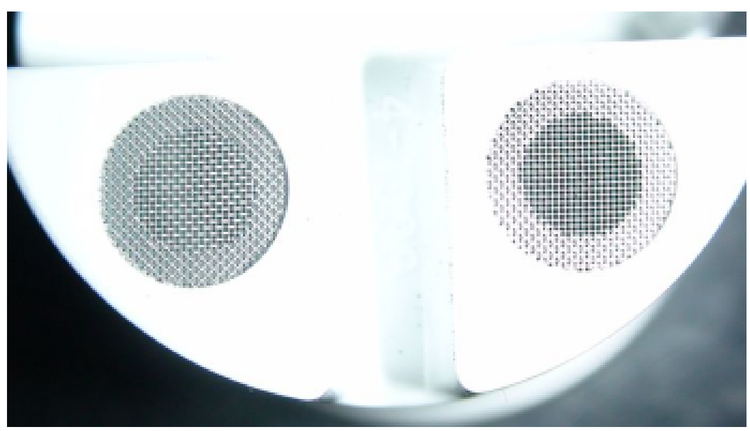

Figure 9 Metal Meshes

5.0 Water Standards

The World Health Organization (WHO) published a guideline for safe drinking water standards [30]. This has been summarized in Appendix A. There are other drinking water guidelines that exist. These include guidelines from Canada [31], and the European Union [32]. The standards from WHO were used because they represent the global drinking water standard. The water filter to be designed should be safe for use in all countries around the world. All water testing results performed in this project will be compared to the recommended values from the WHO guidelines.

6.0 Methodology

As described in Section 4 of the progress report, ceramic filters are inexpensive to make, and a few Engineering without Borders Organization is already producing ceramic filters for people in third world countries [33]. To keep the overall cost similar to that of the existing filters, methods described below are carried out in the development of this low cost, dual water filtration.

6.1 Activated Carbon Manufacturing Methods

Activated carbon can be created from many materials, including nut shells, coal, wood, sewage sludge, tire scrap, paper mill wastes, and natural wastes. All of these materials can go through proper treatment and burning process to create activated carbon [34]. In this thesis, coconut shells are the main source to be considered. Figure 8 shows the activated carbon manufacturing process.

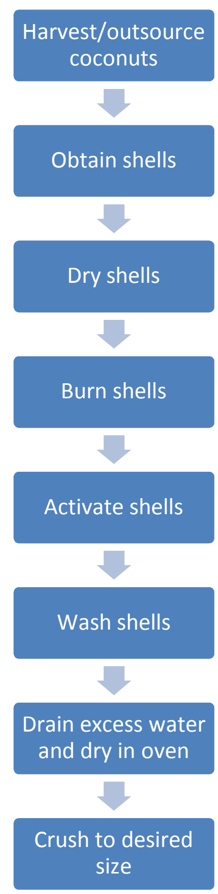

Figure 10 Process of Activated Carbon

Preparation of Shells

Coconuts are harvested in many locations in the world, including Sri Lanka and East Africa [35]. If coconuts are available locally where the filter is manufactured, outsourcing costs can be eliminated for filter production. The Food & Fertilizer Technology Center for the Asian and Pacific Region (FFTC) [36] have guidelines to prepare for carbon activating processes. Coconut shells are separated from the inner material, and dried inside out under the sun.

Burning

Shells are burnt at 300°C for 3 hours. FFTC suggests the use of a kiln or drum burner to obtain the desired temperature. Burning can also be performed with a barbeque stove. The only health concern is that inhaling too much carbon would be harmful for human health.

Activation

Once the shells are burnt to charcoal, they are ready for activation. The FFTC states that burnt charcoal is activated by first soaking it in chemical solutions of either $CaCl_2$ or $ZnCl_2$ for 12-18 hours [36]. The Organic Materials Review Institute states that charcoal should be burnt at a temperatures of 800 to 1,000°C [49] after impregnated with chemicals.

6.2 Ceramic Manufacturing Methods

Making ceramic filter elements is similar to making pottery. The manufacturing process of existing ceramic filters was researched [33]. This thesis will make use of the developed process and modify to suit the needs of this filter design. Table 3 lists the materials required to build the ceramic pot and their purposes for the pot. Table 4 shows the equipments required for building the ceramic level.

Table 3 Materials Required for Building Ceramic Filter Elements

Material	Purpose
Bricks	Main source of material for ceramic mixture
Rice husks	Mixed into ceramic to create pores in order for water to flow through
Water	Used in creating ceramic mixture
Silver nitrate ($AgNO_3$)	Coated on the inner and outer walls of filter to eliminate some bacteria

Table 4 Equipment and Machinery Required for Building Ceramic Filter Elements

Equipment	Purpose
Sledge hammer	Used to crush bricks into powder form
Hand hammer	To crush rice husks into desired size
Stirring tool	To stir clay mixture
Garden bucket	To evenly distribute water over clay mixture during mixing

Scraping tool	To smoothen surface of shaped clay and ensure free of cracks
Kiln/Pottery oven	For firing process

Preparation for Ceramic Mixture – Bricks

The ceramic media of the filter requires the incorporation of rice husks. This allows the water flow rate through the ceramic, while maintaining the effectiveness of filtering water [33]. To obtain the main source of material for the mixture, bricks are initially crushed into pieces with a sledge hammer. The industries put the crushed bricks into a hammer mill to turn the pieces into powder, which will be used in the following steps. Note that the fineness of the powder is not important. If a hammer mill cannot be provided by the thesis industrial partner, bricks will be crushed manually with hammers.

Preparation for Ceramic Mixture – Rice Husks

Rice husks can be purchased from suppliers. Preparation of rice husks requires crushing the rice husks into small pieces. The bigger the husk size, the bigger the pore [33]. For small amounts of rice husks, crushing is performed manually. The use of machines is recommended when mass-producing the filters.

Ceramic Mixture

According to Resource Development International (RDI), a rice husks-to-clay powder ratio of 1:3 is required for the mixture [33]. Water needs to be added in the middle of the mixing process. 1.25L of water is required for every kilogram of rice husks [33]. Clay powder and rice husks must be processed through dry mixing for 10 minutes before water is added. Water is then evenly distributed over the mixture with a gardening bucket, and the mixture should be mixed for 10 additional minutes. Manual mixing is to be used for this project. The use of automatic ceramic mixing machines is recommended for mass production.

Wet clay is then formed manually into shapes of the design. The prototype for this project is to be formed manually. In industries, this step is carried out by hydraulic press machines to form identical shapes for mass production.

Drying and Surface Finishing

Surface finishing is critical. The ceramic surface must be smooth and free of cracks. This ensures the effectiveness of the water filtering process [33]. Scraping tools are useful in this step to scrape off any rough surfaces. After the shape of this particular filter level is formed, the filter is to be air dried. Drying time of the element depends to the size of the filter as well as the drying environment. With filter building experience, RDI recommends to place the filter under a shaded area to ensure a more uniform drying process [33]. Once the filter element is completely dried and hardened it is ready for firing.

Firing

The ceramic part is to be placed in a kiln or pottery oven to complete the firing process. There are two stages in the firing process – dehydration and vitrification. Water molecules are dried off in dehydration under low temperature firing. Vitrification is the process of creating the firm bonds of the ceramics – this is done in higher temperature firing [37]. Rice husks mixed into the clay also burn off, thus creating pores in the pot to allow water to pass through. In industries, numerous filter elements are fired at the same time in a large kiln. The elements are heated at $100^{o}C$ for two hours for drying off water excess within the ceramics [33]. Then, the temperature is gradually increased to $866^{o}C$ over 8 to 10 hours. The firing temperature and time depends heavily on the number of elements and the unique properties of the clay mixture.

For the thesis prototype, the time and temperature for firing will be determined after consultation with pottery experts.

Silver Coating

After the ceramic filter element is fired and cooled, a coating of silver nitrate can be applied on all surface of the element. However, during the water filtration process, there is a risk for the silver solution to dissolve in the filtered water [38]. Investigations have been carried out by Alethia Environmental on how much silver concentration appears in ceramic filtered water. Results have shown that the amount of silver concentration in filtered water depends on the methodology of applying the silver coating onto the ceramic element instead of the initial silver solution concentration [38]. Dartmouth Toxic Metals Research Program also states that silver is not toxic to humans and will not cause cancer or other chronic advert effects [39]. As a result, it is safe to apply a coating of silver solution onto the walls of the filter element.

The following procedure is developed by RDI in the production of their ceramic filters [33]. The amounts used are for approximately 60 flower pot sized ceramic filters by RDI.

1. *Add 100g of $AgNO_3$ (99.8% purity) to 500mL of de-ionized water and then mix well.*
2. *Add 1L of de-ionized water and mix for 1 minute. Silver solution is complete.*
3. *Dilution of Silver solution is done with a silver solution to distilled water ratio of 1:180. (i.e. For every 100mL of silver solution used, it should be diluted with 18L distilled water)*
4. *Using a paint brush, silver solution is coated on the inside and outside of the filter.*
5. *Let dry.*

6.3 Method of Testing

The objective of this low cost water filter design is to provide safe drinking water to a small family in the third world places. Thus, the product's effectiveness in filtering contaminants is critical. At the same time, the filter flow rate must be optimized to provide clean water in a reasonable amount of time. Two tests had been carried out to justify these factors. Water samples were analyzed by Maxxam Analytics for filtering effectiveness. A series of water flow rate tests were conducted to find the optimal value. The required materials and procedures utilized in both tests are described in the following sections.

6.3.1 Flow Rate Test

The relationships between filter flow rate and ratio of ceramic mixture were established through the flow rate test. Two types of additives were considered, sawdust and wheat flour. The goal was to find the optimal mixture ratio that would maximize flow rate. In this experiment, ceramic filter elements with sawdust-ceramic ratios of 10%, 20%, 30% and with wheat flour-ceramic ratios of 10%, 20%, 30%, 40% and 50% were tested. In order to control the consistency of the test, all testing water was from the same source. The following materials were required to conduct the flow rate test for each filter prototype:

- Ceramic filter element built with mixture ingredients (1)
- Measuring beaker (1)
- Lake Ontario water (100mL)
- Plastic container (1)
- Cap (1)
- Plastic food wrap (1 piece)
- Stopwatch (1)

The following procedure was carried out to complete a flow rate test.

1. Obtain a built ceramic filter element with a particular ingredient.
2. Use a measuring beaker to obtain 100mL of water from Lake Ontario.
3. Pour 100mL of water into ceramic filter element.
4. To ensure minimal evaporation, enclose the setup of the testing filter with a cap and seal off the openings with plastic food wrap.
5. Start the stop watch to begin timing and stop when all the water has gone through the filter.
6. Repeat steps 1-5 for each ceramic filter element.
7. Record and graph result.

6.3.2 Test for Filter Effectiveness

The effectiveness of filtering contaminants was tested by Maxxam Analytics, who is a licensed laboratory for high quality water testing. Based on the standards of safe drinking water, 200 mL of water sample was collected for the "Metals Test", 200 mL for the "Nutrients Test", and 500 mL for the "General Test". This requirement held true for all samples that were tested. Water directly from Lake Ontario was tested to determine what was contained. The same water that had gone through the activated carbon level was tested to see what elements were eliminated or reduced in the carbon filtering level. The same water that had gone through the dual filter – ceramic and carbon, was tested for the overall analysis. By completing the above three analyses, elements that were filtered out in each level of the dual filter would be identified. The fourth sample was filtered tap water with the Brita filter; this analysis serves as a reference for other samples. The tests conducted on each type of water sample are summarised in Table 5.

Table 5 Tests Conducted from Various Water Sources

	Unfiltered Lake Ontario Water	**Lake Ontario Water (Carbon)**	**Lake Ontario Water (Dual)**	**Tap Water (Carbon)**
Nutrients	✓	✓	✓	✓
Metals	✓	✓	✓	✓
General	✓	✓	✓	✓

The following materials were used to prepare the samples for Maxxam Analytics.

- Ceramic filter element (1)
- Carbon filter element
- Lake Ontario water (Figure 11)
- Plastic container for storage of filtered water
- Filter cap
- Plastic food wrap
- 2x 200mL plastic bottles with screw-cap provided by Maxxam Analytics (Figure 12)
- 1x 500mL plastic bottle with screw-cap provided by Maxxam Analytics

- Ice pack
- Cooler

Figure 11 Bottled Water from Lake Ontario

Figure 12 Bottles from Maxxam Analytics

The following procedure was carried out to complete the effectiveness test on the dual filter.

1. Place activated carbon elements into a fully built ceramic filter element.
2. Fill up the dual filter with water from Lake Ontario. Ensure absolutely no spilling on the apparatus for accurate analysis. Due to a relatively slow flow rate, it is recommended to setup a number of dual filters and allow them to filter in parallel.
3. To ensure minimal evaporation, enclose the setup of the testing filter with a cap and seal off the openings with plastic food wrap.
4. Fill the two 200mL plastic bottles with filtered water. One bottle is for metals test while the other for nutrients test.
5. Fully close the bottles with the screw-cap and place in refrigerator at less than 10°C until shipment as per Maxxam Analytics instructions.
6. Fill the 500mL plastic bottle with filtered water. This bottle is for the general test.
7. Fully close the bottle with the screw-cap and place in refrigerator at less than 10°C until shipment as per Maxxam Analytics instructions.
8. Repeat steps 2-7, if necessary, until the bottles are filled up to the fill-line indicator on the bottles.
9. Package the sample bottles in the provided cooler with an ice pack. This maintains the required low temperature condition during the shipment of the samples to Maxxam Analytics.
10. Ship samples to Maxxam Analytics for analysis.

The following procedure was carried out to complete the effectiveness test on the carbon filter with Lake Ontario water and tap water.

1. Pour unfiltered Lake Ontario water into a typical home-use carbon filter (eg. Brita carbon filter).
2. Allow it to complete the filtering and fill up to the fill-line indicator on the two 200mL plastic bottles with filtered water. One bottle is for metals test while the other for nutrients test.
3. Fully close the bottles with the screw-cap and place in refrigerator at less than 10°C until shipment as per Maxxam Analytics instructions.
4. Fill up to the fill-line indicator on the 500mL plastic bottle with filtered water. This bottle is for the general test.
5. Fully close the bottle with the screw-cap and place in refrigerator at less than 10°C until shipment as per Maxxam Analytics instructions.
6. Package the sample bottles in the provided cooler with an ice pack. This maintains the required low temperature condition during the shipment of the samples to Maxxam Analytics.
7. Repeat steps 1-6 for unfiltered tap water.
8. Ship samples to Maxxam Analytics for analysis.

The following procedure was carried out to complete the effectiveness test on the unfiltered Lake Ontario water.

1. Fill up to the fill-line indicator on the two 200mL plastic bottles with unfiltered water. One bottle is for metals test while the other for nutrients test.
2. Fully close the bottles with the screw-cap and place in refrigerator at less than 10°C until shipment as per Maxxam Analytics instructions.
3. Fill up to the fill-line indicator on the 500mL plastic bottle with unfiltered water. This bottle is for the general test.
4. Fully close the bottle with the screw-cap and place in refrigerator at less than 10°C until shipment as per Maxxam Analytics instructions.
5. Package the sample bottles in the provided cooler with an ice pack. This maintains the required low temperature condition during the shipment of the samples to Maxxam Analytics.
6. Ship samples to Maxxam Analytics for analysis.

7.0 Design & Prototyping

7.1 Prototyping

Before a final design of the water filter was created, it was necessary to ensure that the filter works as described. Several filters were made to determine the filter effectiveness and flow rate using different additives ratio. Table 6 lists the ratios of combustible material mixed for the prototypes. Note that sawdust and wheat flour were used as substitutes for rice husks because rice husks could not be sourced locally.

Table 6 Prototype Filter Ratios

Batch	Sawdust Ratio [%]	Wheat Flour Ratio [%]
1	10, 20	10, 20
2	-	30, 40, 50, 60
3	-	30, 40, 50, 60
4	30, 50	-

A total of fourteen prototypes were made. To ensure accuracy, two beakers were used to measure the volume of clay being mixed with the combustible material. Figure 13 shows a 50-50 ratio using wheat flour.

Figure 13 Ratio Mixing Beakers

Figure 14 shows the completion of a ceramic prototype. Each prototype had been marked as shown in Figure 15. In this example, “20W1” denotes a 20% wheat flour (W) ratio made in batch 1. Completed prototypes were then sent to Little Big Arts School for firing.

Figure 14 Completed Ceramic Prototype

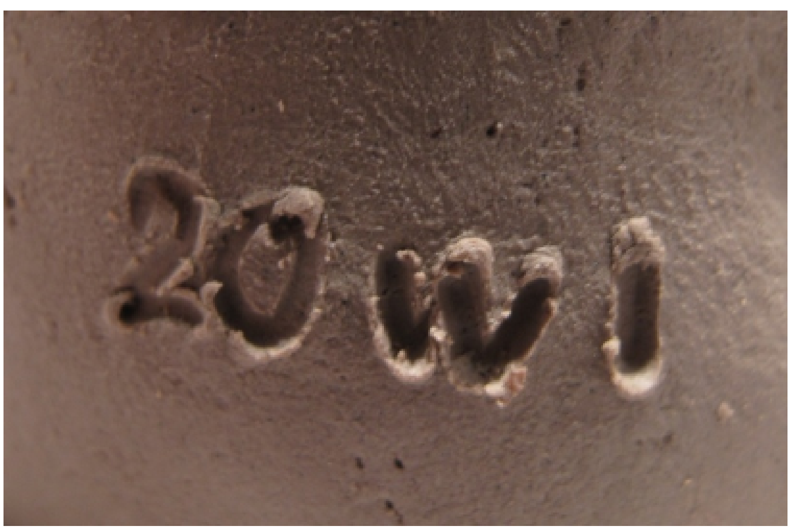

Figure 15 Notation on Ceramic Prototypes

7.2 Concept Sketches

Figures 16 and 17 illustrate the two concept sketches that were determined to be most feasible for use in third world countries.

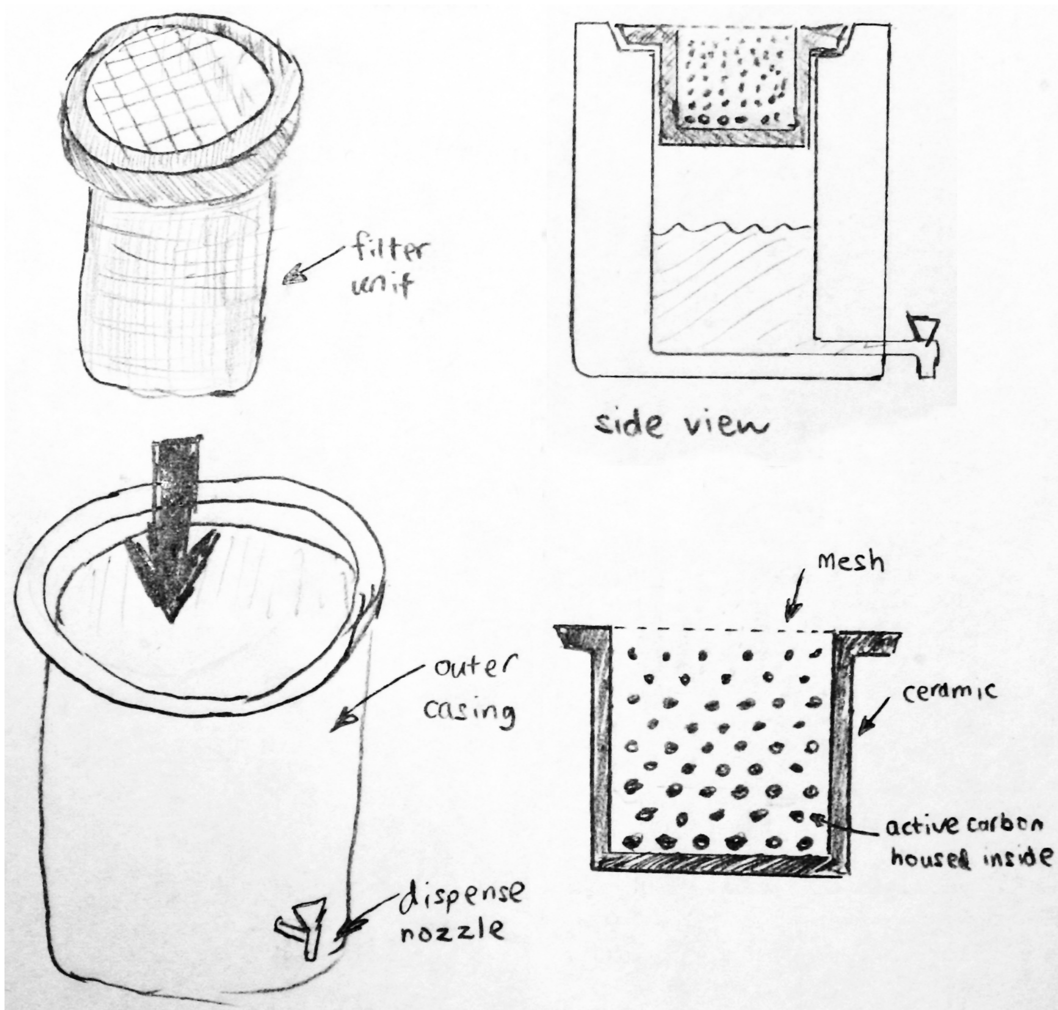

Figure 16 Concept Sketch 1

Concept 1 shows the ceramic filter being placed inside a casing. This is similar to the design of many Brita water filters. Water is poured in through the top, where a fine mesh filters out large particles such as pebbles. The mesh also locks the activated carbon elements housed inside the ceramic filter. Water goes through both filtering methods and collects at the casing. Users can then dispense clean water through the nozzle.

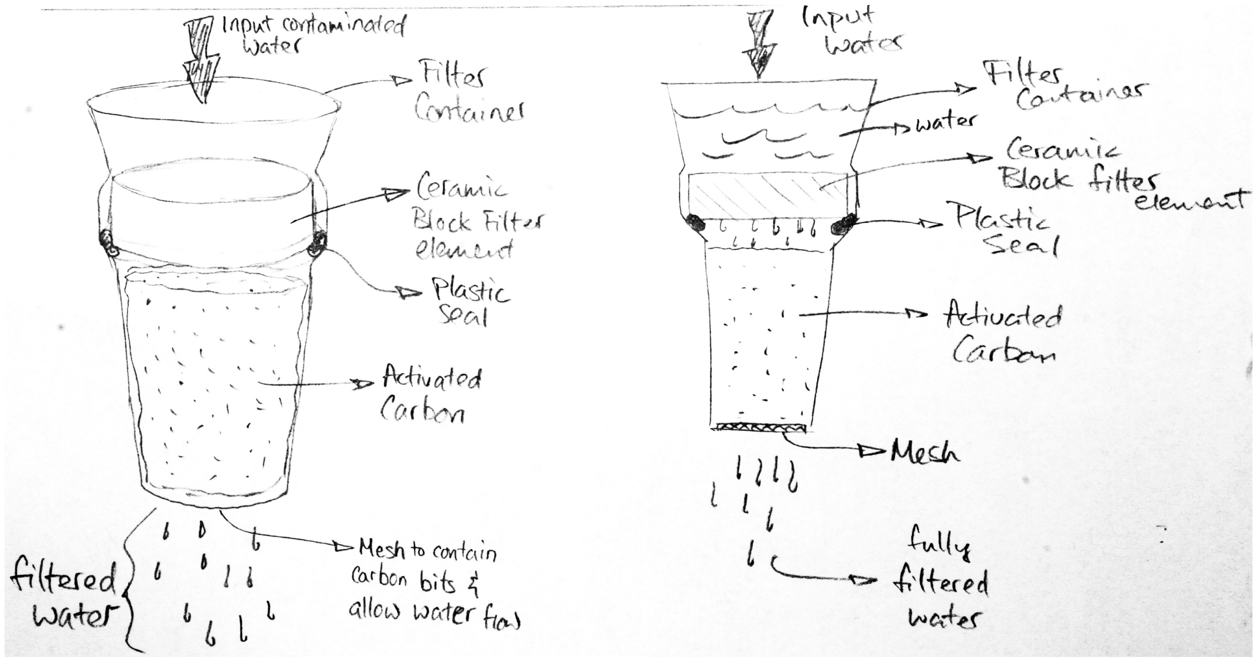

Figure 17 Concept Sketch 2

The second concept is based on the design of the Brita activated carbon filtering module as discussed in Section 4.8. Activated carbon will be housed in a container. There will be a mesh at the bottom so only water can pass through. The container is designed so that the ceramic filter will sit flush on top. Since the ceramic filter is separate, no mesh at the top is necessary to separate pebbles. The user can simply empty the remaining contents inside the ceramic filter afterwards, and also clean the filter with a brush. This design also allows separate replacement of the ceramic filter and the activated carbon granules. However, this poses a risk of the user using only one of the two filters.

The mesh in concept 1 prevents the user from cleaning the ceramic filter. Therefore, the amount of activated carbon placed inside should just be enough so that both elements of the unit need to be replaced at the same time.

8.0 Testing

8.1 Flow Rate Test

Ceramic filter elements with sawdust ratios of 10%, 20%, 30% and with wheat flour ratios of 10%, 20%, 30%, 40% and 50% were tested for their corresponding flow rates. The relationship between the ingredient ratios and filter flow rate is shown in Figure 18.

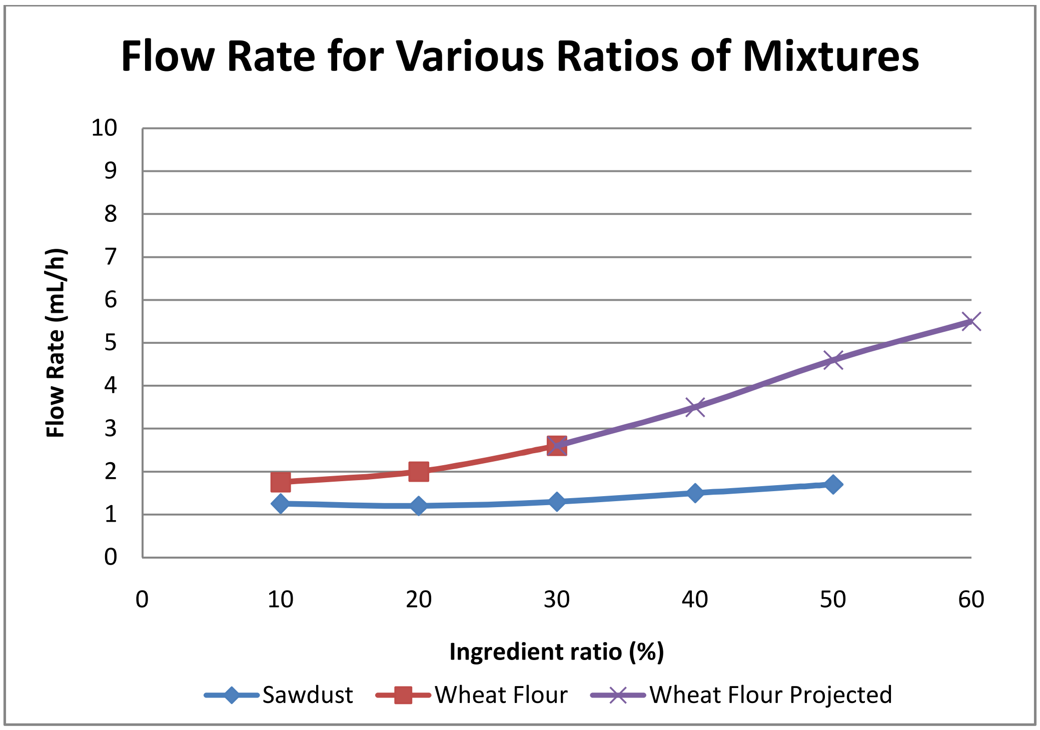

Figure 18 Flow Rate Curves for Ceramic Filters of Various Ratios

Results have shown that the sawdust ingredient did not have a noticeable effect on the filter flow rate as the slope is fairly flat. Data was obtained for only 10%, 20%, and 30% of wheat flour mix because of the technical problems encountered during the firing process for 40% and above. These issues are discussed in Section 11. Data for wheat flour suggests that it is a more sensitive ingredient for increasing flow rates. The flow rates for 40% and above were extrapolated based on the trend obtained from the smaller ratios.

Out of the two tested ingredients, sawdust did not have significant influence on the flow rate but it was the more reliable ingredient. The wheat flour mix had improvements on the larger mixture ratios but the consistency at the processing stage is a setback; this would become an issue at production.

8.2 Filter Effectiveness

Regardless of the slow flow rate, enough filtered water was collected for Maxxam Analytics to perform sample analyses. Maxxam Analytics had completed three tests for each water sample: Metals, Nutrients, and a General test. In the metals test, numerous elements such as Aluminum, Magnesium, Sodium, etc. were assessed. In the nutrients test, the presence of Total Organic Compound (TOC), Total Phosphorus, Nitrate, and Nitrite were measured. In the General test, turbidity, pH level, conductivity, alkalinity, colors, and Ammonia were measured. The results indicated the decrease or increase on each tested element after the carbon filter level and after the dual filter level. It also presented the benefits with the use of a dual filter design as it provided cleaner drinking water. Results were compared to the standards from World Health Organization (WHO) and to the reference sample of tap water going through carbon filtering.

8.2.1 Nutrients Test

The concentrations of inorganic components within each water sample were determined in this nutrients test. Results are tabulated in Table 7.

Table 7 Concentrations of Inorganic Components for Each Filter Level

Inorganics	Units	Lake Ontario (Original)	Lake Ontario (Carbon)	Lake Ontario (Combined)	Tap Water (Carbon)
Total Ammonia	mg/L	0.65	4.5	0.73	0.61
Conductivity	µmho/cm	392	348	285	268

Total Organic Carbon (TOC)	mg/L	2.7	3.7	1.4	1.6
Orthophosphate	mg/L	ND	0.14	2.5	0.28
pH	pH	7.8	3.3	7.3	6.8
Total Phosphorus	mg/L	0.022	0.14	2.9	0.37
Dissolved Sulphate (SO_4)	mg/L	27	8	20	28
Turbidity	NTU	0.8	1.4	0.4	0.5
Alkalinity (Total as $CaCO_3$)	mg/L	91	ND	57	41
Dissolved Chloride (Cl)	mg/L	39	65	30	27
Nitrite (NO_2)	mg/L	0.08	ND	0.04	ND
Nitrate (NO_3)	mg/L	0.9	ND	0.1	0.1

Total Organic Compound

Tables A-2 and A-3 in Appendix A are WHO standards of organic compound and disinfectants byproducts, respectively. In order to complete full analysis on the listed elements, relatively expensive chemical tests are required. Maxxam Analytics generalized this into the simpler Nutrients test for inorganic materials. The presence of organic compounds indicates the amount of disinfectants in the test. According to United States of Environmental Protection Agency [41], disinfectants react with natural organic matters (NOM) in water to form disinfection byproducts (DBP) which is harmful for human health. Total Organic Compound (TOC) is the indicator for the presence of natural organic matters (NOM) in water and DBP formation and exposure can be reduced when TOC concentration is lowered [41]. Therefore the TOC measurements provided in the sample tests were used to generalize the presence organic matters and disinfectants. Data suggests that the dual filter reduced TOC to 1.4mg/L, a 48% reduction. This brought water from Lake Ontario to a similar level of a typical home filtered tap water with 1.6mg/L of TOC detected.

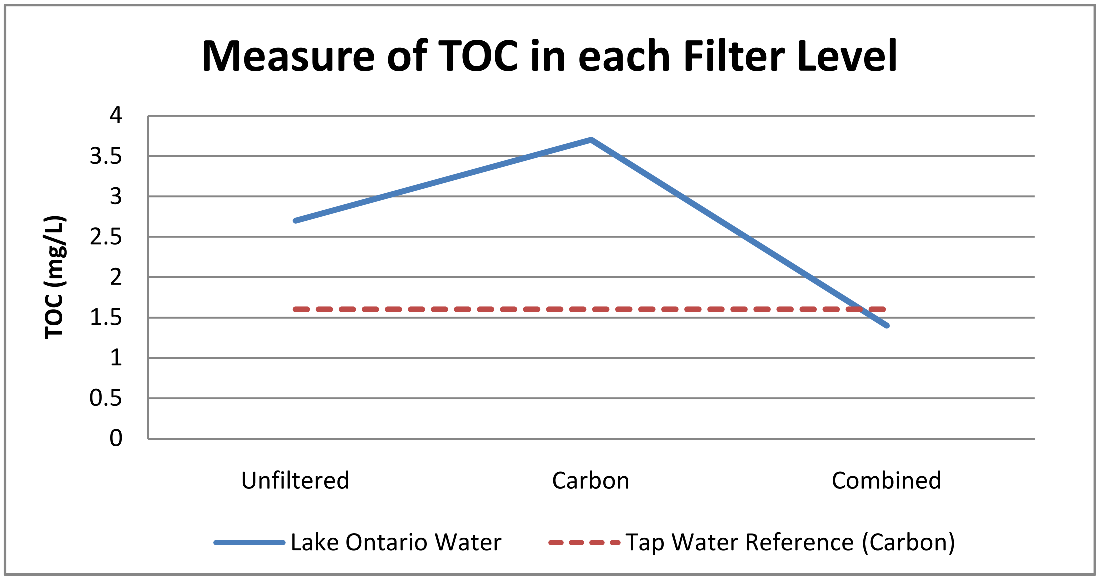

Figure 19 TOC Measurements for Each Filter Level

<u>Phosphorus and Orthophosphate</u>

Phosphorus and Orthophosphate (OP) is a corrosion inhibitor commonly used in big cities such as New York City and Detroit [42]. It is added in pipelines to prevent lead from leaching into drinking water which could potentially cause harm to health [42]. However, the possibility for third world places to have similar pipeline treatments is minimal. Phosphorus and Phosphates are healthy for humans if not excessively consumed [42]. Health impacts occur if a 150 pound adult consumes more than 5000mg/day, approximately 1400mg/day for a 40 pound child [42]. Results indicated that the OP and phosphorus contents had increased to only 2.5mg/L and 2.9mg/L, respectively, after the filtering. This is well under the harmful limit as a typical adult drinks about 2L of water a day to prevent dehydration [8].

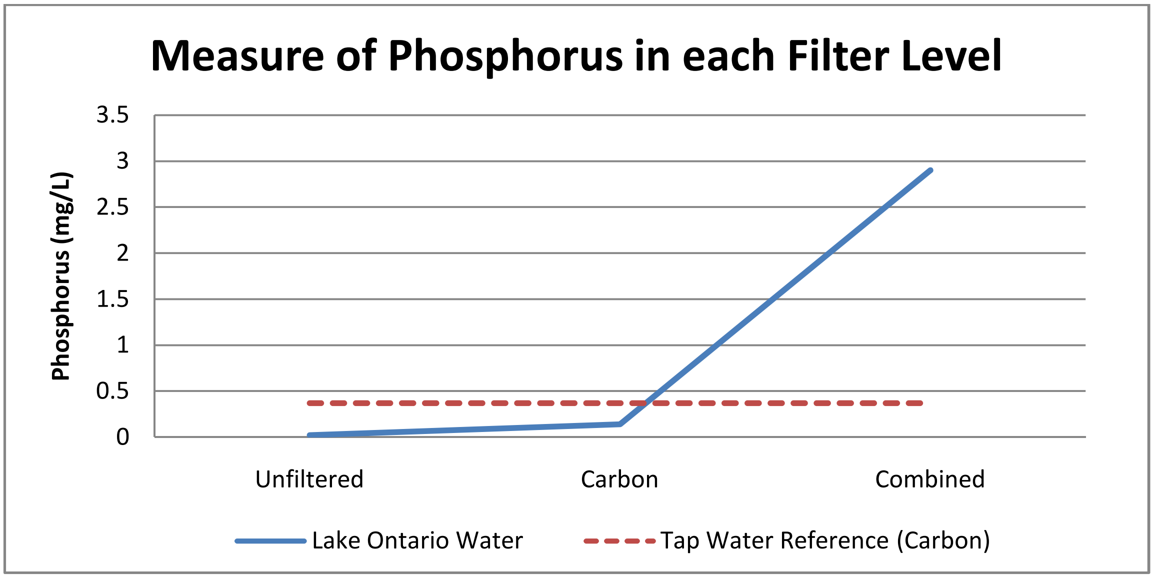

Figure 20 Phosphorus Measurements for Each Filter Level

Nitrate and Nitrite

Nitrate and nitrite concentration in drinking water is a common pollution in developed countries. According to World Health Organization [44], nitrate and nitrite create a formation of methaemoglobinaemia, also known as blue-baby syndrome. This is harmful to infants as nitrite would stop the transfer of oxygen within the body [44]. Nitrates are a major chemical used in inorganic fertilizers and nitrites are used in food preservations [44]. Nitrate concentration could seep to surface water from agriculture areas. Some of the third world agriculture may only have little contact with fertilizers, but nitrate concentration would also occur from contamination from human or animal wastes as a result of the oxidation of ammonia [44]. Thus, a filtration in nitrate and nitrite is essential.

Although testing the effectiveness with surface water from third world countries would be ideal to provide more persuasive results, the water from Lake Ontario satisfies the test for removing nitrate and nitrite. Results from sample analysis proved that the dual filter was capable of removing 88.9% of nitrate and 50% of nitrite.

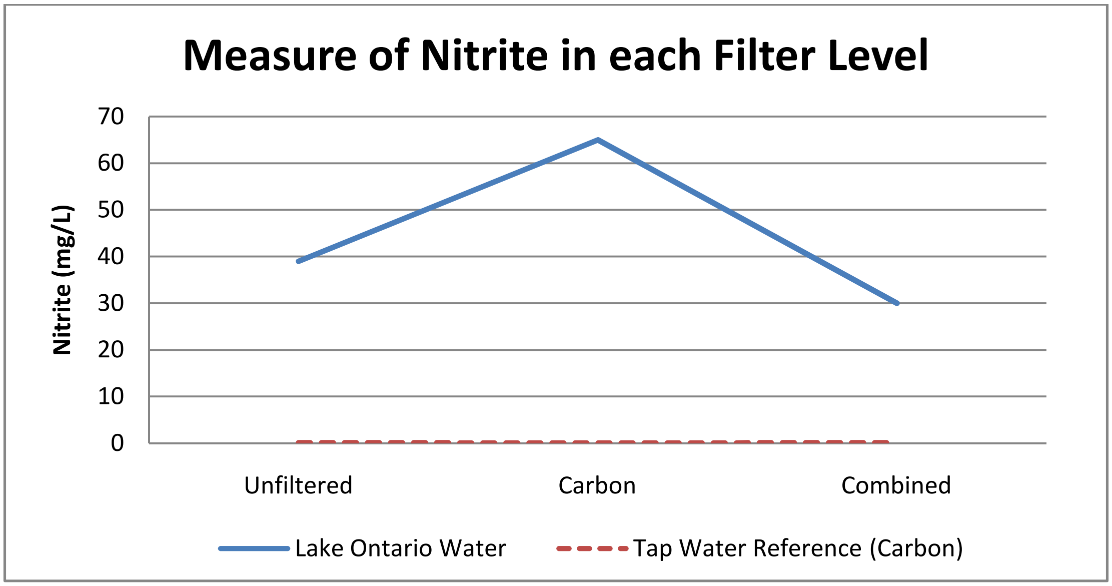

Figure 21 Nitrite Measurements for Each Filter Level

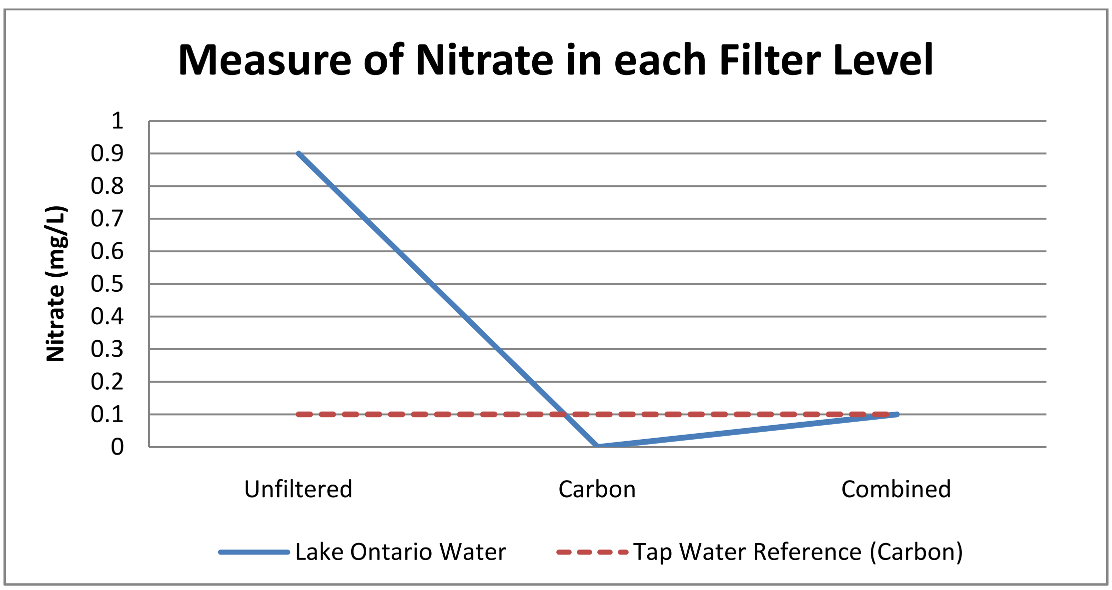

Figure 22 Nitrate Measurements for Each Filter Level

Are Ceramic Filters Needed?

For most of the tested components, the dual filter showed significant improvement in water quality. It is evident that an activated carbon filter is not enough to provide safe drinking water to filter surface water. The pH, alkalinity, TOC, and turbidity had risen for Lake Ontario water processing through just the carbon level. With the addition of the ceramic filter, the above elements have reduced significantly to match that of the reference filtered tap water. The dual filter design definitely increased filter effectiveness.

8.2.2 Metals Test

The concentrations of a number of metals within each water sample were determined in this metals test. Results are tabulated in Table 8.

Table 8 Concentrations of Metals for Each Filter Level

Metals	Units	Lake Ontario (Original)	Lake Ontario (Carbon)	Lake Ontario (Combined)	Tap Water (Carbon)
Dissolved Calcium (Ca)	mg/L	35.4	2.95	5.12	0.07
Dissolved Magnesium (Mg)	mg/L	8.27	1.77	2.89	ND
Dissolved Potassium (K)	mg/L	2	ND	31	38
Dissolved Sodium (Na)	mg/L	24.7	19.8	24.6	25.7
Total Aluminum (Al)	µg/L	56	36	16	15
Total Antimony (Sb)	µg/L	ND	ND	1.2	ND
Total Arsenic (As)	µg/L	ND	15	24	ND
Total Barium (Ba)	µg/L	23	ND	21	ND
Total Beryllium (Be)	µg/L	ND	ND	ND	ND
Total Boron (B)	µg/L	18	31	150	ND
Total Cadmium (Cd)	µg/L	ND	ND	ND	ND
Total Calcium (Ca)	µg/L	38,000	2,800	6,900	ND
Total Chromium (Cr)	µg/L	ND	ND	ND	ND
Total Cobalt (Co)	µg/L	ND	ND	ND	ND
Total Copper (Cu)	µg/L	2	ND	4	4
Total Iron (Fe)	µg/L	ND	ND	ND	ND
Total Lead (Pb)	µg/L	ND	ND	ND	ND
Total Magnesium (Mg)	µg/L	9,300	1,800	4,200	ND
Total Manganese (Mn)	µg/L	3	2	ND	ND
Total Molybdenum (Mo)	µg/L	1	ND	46	ND
Total Nickel (Ni)	µg/L	ND	6	ND	ND
Total Potassium (K)	µg/L	2,100	580	9,800	38,000

Total Selenium (Se)	µg/L	ND	ND	ND	ND
Total Silicon (Si)	µg/L	590	890	29,000	770
Total Silver (Ag)	µg/L	ND	ND	ND	ND
Total Sodium (Na)	µg/L	26,000	20,000	23,000	26,000
Total Strontium (Sr)	µg/L	190	14	68	ND
Total Thallium (Tl)	µg/L	ND	0.10	ND	ND
Total Titanium (Ti)	µg/L	ND	ND	ND	ND
Total Uranium (U)	µg/L	0.4	ND	0.4	ND
Total Vanadium (V)	µg/L	ND	ND	470	ND
Total Zinc (Zn)	µg/L	ND	ND	6	ND

**ND – Not detectable*

In order to fully understand the quality in the surface water from third world countries, on-site water sampling is ideal. Due to the lack of access, information on the water quality from Lake Victoria, Kenya by Aquatic Ecosystem Health & Management [43] was used in the comparison. It is assumed that the information is still valid, despite the data being collected back in 1994. Monthly analyses were conducted on the water from various rivers that links to Lake Victoria in Kenya. Zinc, lead, copper, cadmium, iron, chromium, manganese, and aluminum were measured. Table 9 compares the metals concentration in Kenya's water to the concentrations measured from Lake Ontario's samples.

Table 9 Comparison of Detected Metals with Water from Lake Victoria, Kenya

Metals	Lake Victoria, Kenya (Highest detection) [µg/L]	Lake Ontario (Before) [µg/L]	Lake Ontario (After) [µg/L]	WHO/USEPA Limits [µg/L]
Zn	1.2	Not detected	6	5,000
Pb	20	Not detected	Not detected	10
Cu	40	2	4	2,000
Cd	Not detected	Not detected	Not detected	3
Fe	20,100	Not detected	Not detected	300
Cr	50	Not detected	Not detected	50
Mn	107	3	Not detected	40
Al	20,040	56	16	200

Results show that copper amounts increased after water from Lake Ontario was processed through the dual filter. However, the increase did not exceed the safe water drinking standards from WHO as the limit is 2,000µg/L.

Iron and aluminum are the two major metals present in water from Lake Victoria. Iron concentration was recorded to be 20,100µg/L while aluminum was 20,040µg/L. Iron helps transport oxygen through human blood. While it is not considered hazardous to human health, it leaves a reddish colour to the water [45]. The USEPA limit of 300µg/L ensures that water meets aesthetic expectations [46]. However, iron was not detected in the original water from Lake Ontario, thus the effectiveness of filtering iron cannot be analyzed. Aluminum delivers no harm to health but stains the water; the limit is 200µg/L [46]. Results show that the filter eliminates approximately 71% of aluminum. Assuming the same effectiveness, the filter may decrease the amount of aluminum to approximately 5811µg/L in water from Lake Victoria. This value still exceeds the limit.

There are setbacks with the water source used to perform the metals test because water from Lake Ontario seems to be free of toxic metals; zinc, lead, cadmium, iron, and chromium are not detected originally. This does not provide a clear view as to whether the filter is effective at eliminating those metals. It is highly recommended to obtain water samples from third world countries to yield a conclusion on the filter's effectiveness in screening metals.

8.2.3 General Test

Conductivity

Conductivity is a measure of the ability of water to carry electric current. This measure detects the amount of dissolved solids in water and has an influence of the water taste [47].

Results show that the carbon filter level reduced 11% of conductivity. With the introduction of the ceramic filter, conductivity was reduced by 27%.

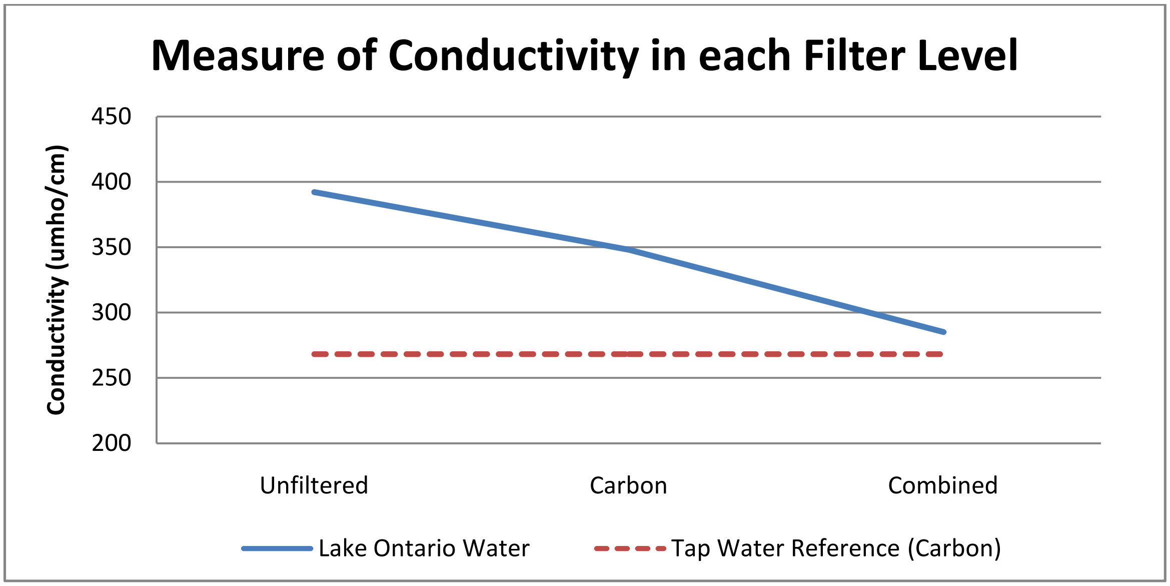

Figure 23 Conductivity Measurements for Each Filter Level

pH and Alkalinity in Drinking Water

The pH level of water is an indicator of how acidic or basic the water is. The pH of Lake Ontario water measured to be 7.8. When it was filtered through the carbon level, the pH level had decreased significantly to 3.3. This is at the far end of the acidic side of the spectrum. Water that has pH level of 5 or below would introduce corrosion in metals [48]. When the water went through the ceramic filter, the pH level measured to be 7.3.

Alkalinity is the measure in the capability of water to neutralize acids [48]. It is normally expressed as a concentration of calcium carbonate ($CaCO_3$) and there is no drinking water quality guideline for alkalinity concentration [48]. The reason for the sudden drop in pH level can be explained by the absence of alkalinity. Analysis from Maxxam Analytics indicated Alkalinity was not detected in the water filtered through just the carbon filter. Alkalinity was reintroduced in the dual filter where the ceramic filter is present; hence the higher pH level. The drinking water guideline for pH level is between 6.5 and 8.5. Therefore, the final quality of the water falls within the limit.

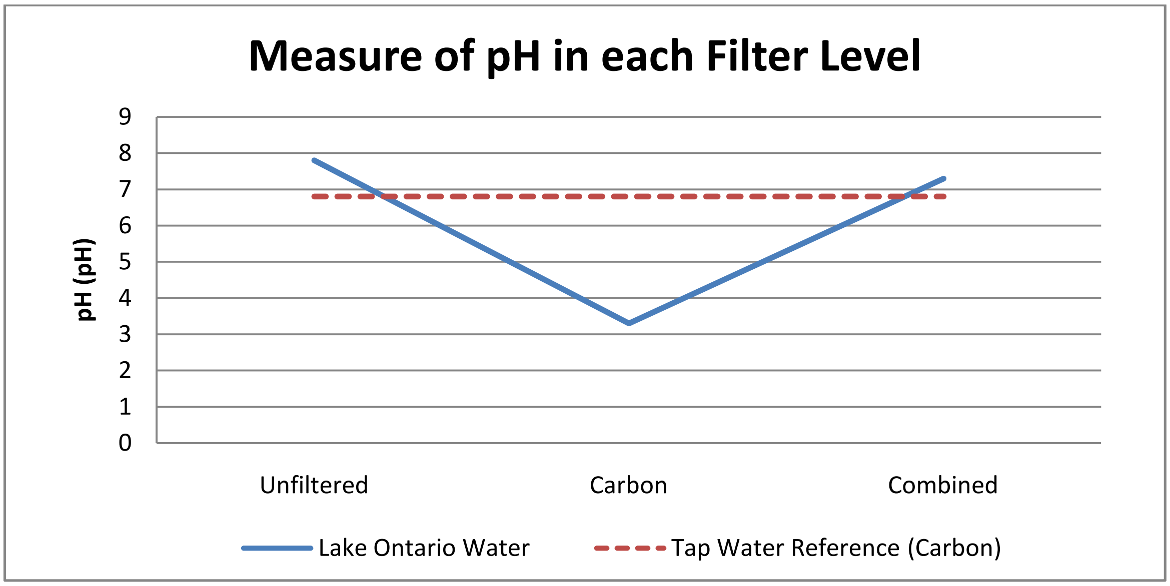

Figure 24 pH Measurements for Each Filter Level

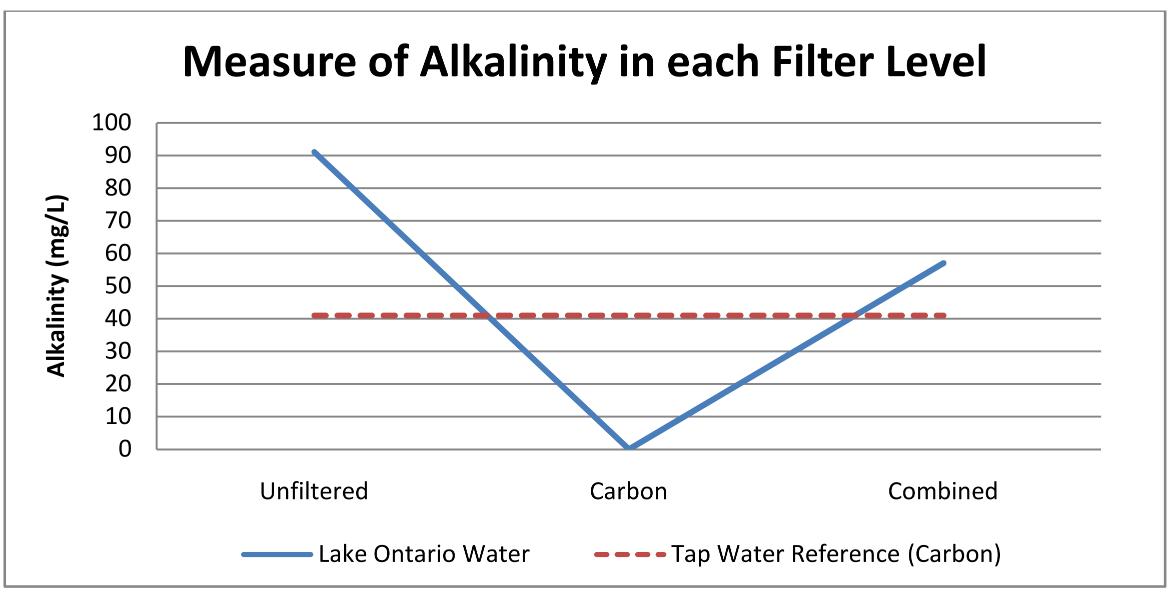

Figure 25 Alkalinity Measurements for Each Filter Level

Turbidity

The aesthetics of the water is an important factor for many people, especially people from the third world places. The turbidity of the water suggests the purity of it. Lake Ontario water processed through the dual filter was 50% clearer with a measure of 0.4 NTU, making it less turbid than typical home filtered tap water.

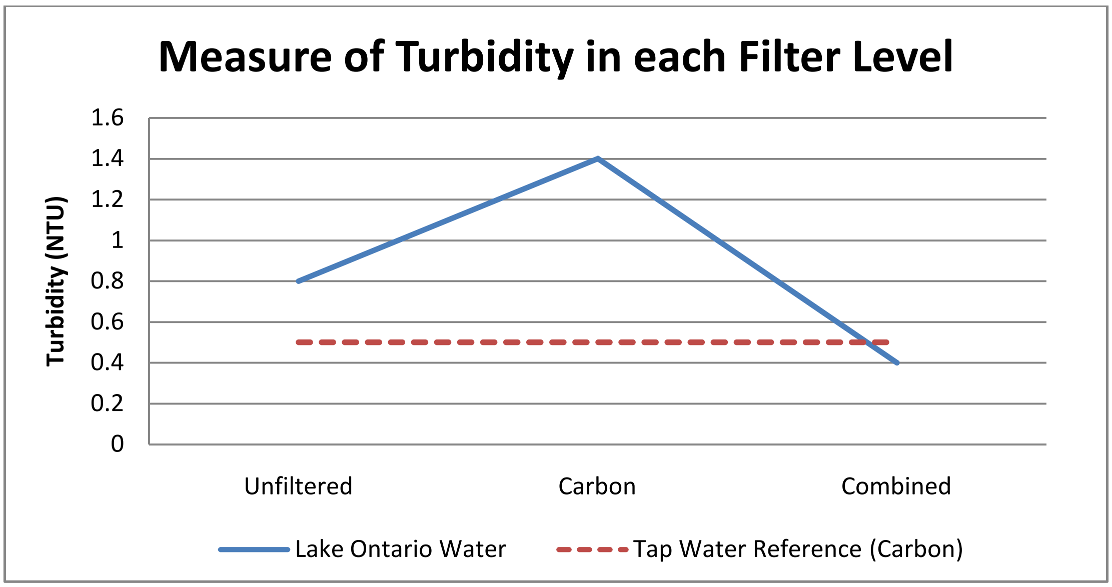

Figure 26 Turbidity Measurements for Each Filter Level

9.0 Final Design

The final design of the low cost water filter concept is very similar to that of Concept 1 in section 7.2. Figure 27 shows that the ceramic filter is placed inside a metal or plastic casing. Water is poured into the ceramic filter, where the fine mesh at the top separates large sediments such as pebbles. Activated carbon elements are housed inside the filter, and locked in place by the mesh. Water is dually filtered, comes out through the ceramic, and is collected inside the casing.

A dispense nozzle at the bottom of the casing allows easy access to the filtered water. This is important as the size of the bucket measures to be 250mm diameter by 400mm in height. Disregarding the volume taken up by the ceramic filter, this design holds roughly 9.8 litres of water, and will be too heavy to be lifted for the pouring of water. Using the daily intake of 2L per person per day, a family of 8 will need to fill up the container twice every day. A design with larger dimensions means that families will have to refill the container less frequently. However, this is not recommended because water kept in the tank for long periods of time may become stagnant and promote the growth of bacteria.

The ceramic filter is designed to fit inside the casing. However, edges on the side of the filter prevent it from falling through. A user can also easily remove the filter for replacement. The amount of activated carbon to be added will be calculated so that the lifespan of these granules and the ceramic will be identical. This increases the ease of use for the users as there is no need to keep track of two replacement schedules.

The flow rate of this filter was calculated to be 0.003 m^3 per hour, or 83 litres per day. Refer for Appendix B for detailed calculations.

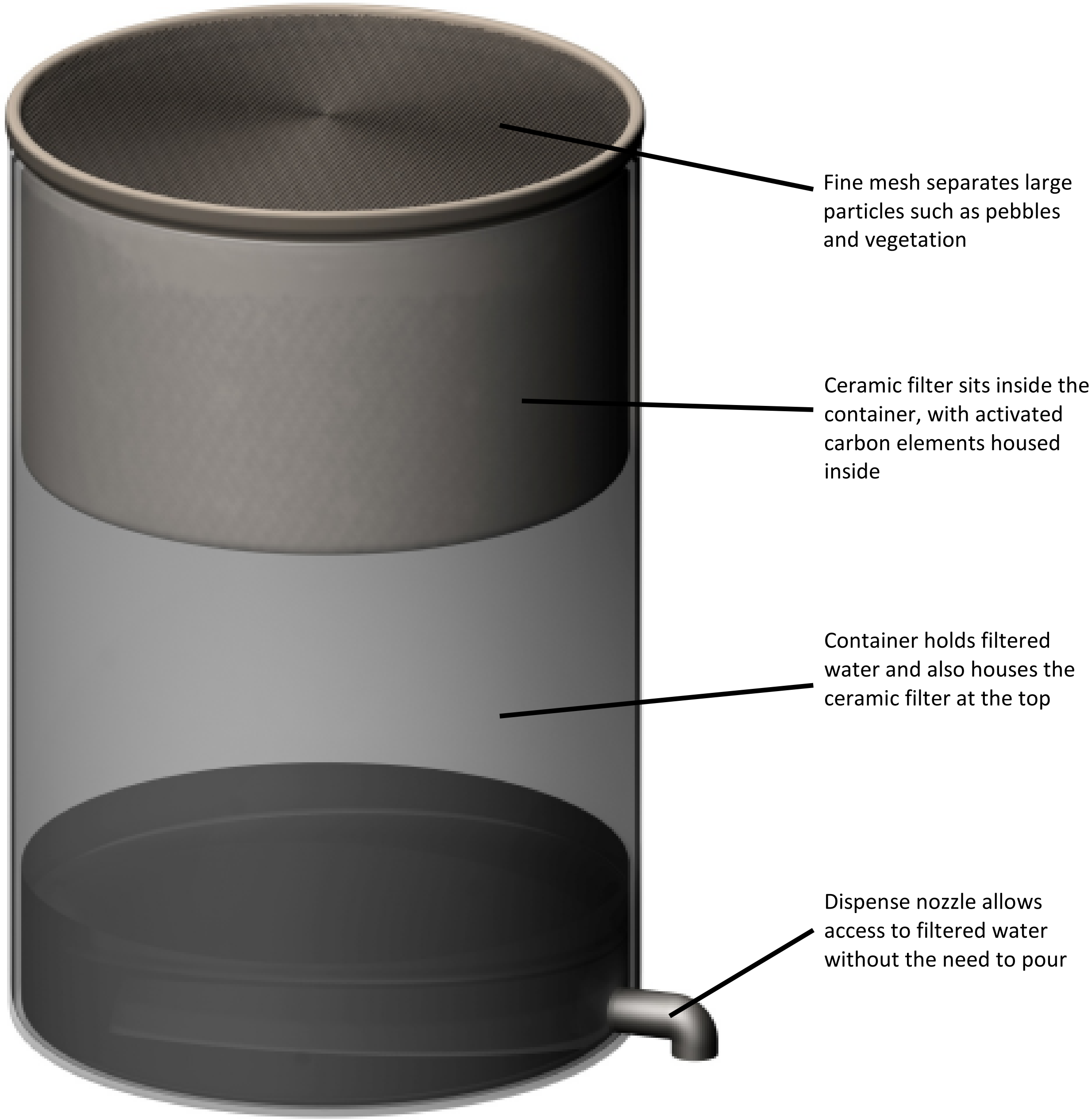

Figure 27 Dual Filter Final Design Rendering

10.0 Economic Analysis

The gross national income per capita in Kenya is only $680 USD [50]. As proposed by the industrial partner, the target sale price for the dual filter is $2 USD. An economic analysis was conducted to estimate the production cost of the filter.

<u>Ceramic Filter</u>

The manufacturing line for making the ceramic filters consist of a hydraulic press, ceramic kiln, clay mixer, and other tools. Further, a total of four workers are to be hired to work at each station. The following assumptions apply for calculating an estimated cost of making the ceramic filter level.

- Manufacturing line operates at 8 hours a day, 5 days a week, 50 weeks a year
- A total of 100 ceramic filter elements will be produced each day
- A total of 125,000 filters will be produced in 5 years of operation

Tables 10, 11, and 13 illustrate the material, equipment, and operating costs required to operate a production line to manufacture the ceramic filters over five years.

Table 10 Material Costs for Running the Ceramic Production Line for Five Years

Materials	Cost ($ USD)	Remarks
Clay	7,500.00	Purchased locally
Water	0.00	Surface water
Sawdust/Rice Husk	500.00	Purchased from India
Total Material Cost	8,000.00	

Table 11 Start-up Equipment Costs for Running the Ceramic Production Line

Equipment	Qty	Cost ($ USD)	Model
Clay Crusher	1	10.00	Custom made hand tool
Hammer Mill	1	1,680.00	Meadows #5 Hammer Mill [51]
Clay Mixer	1	4,082.00	Bailey: C-119-200 [52]
Misc. Tools (Shelves, Buckets, Brushes)	1	200.00	Tools with basic functionality
Hydraulic Press with Mold	1	542.85	Draper HBP/10 [53]
Kiln	1	5,950.00	L&L Kilns: TB3418-D [54]
Total Equipment Cost		12,464.85	

Power required for the hammer mill, clay mixer, and the kiln are 10 kW, 4.584kW and 19.935kW respectively [51], [52], [55]. Referring to the assumptions made earlier, the manufacturing line would run for 2,000 hours a year. The cost of electricity in Kenya, as of September 28, 2008, is Ksh 15/kWh [56]. This is equivalent to $0.19 USD/kWh as of March 25, 2009 [57]. Therefore, the total energy cost is $13,117.22. This is summarized in Tables 12 and 13 for the calculation of operating costs.

Table 12 Electricity Costs for Running the Ceramic Production Line for Five Years

Machine	Power (kWh)
Hammer mill	20,000
Clay mixer	9,168
Kiln	39,870
Total Power	69,038
Total Electricity Costs	$13,117.22

Table 13 Operating Cost for Running the Ceramic Production Line for One Year

	Qty	Cost ($ USD)
Workers	4	2,720.00
Power Consumption	-	13,117.22
Total Operating Cost		15,837.22

Table 14 Unit Cost Summary for Production of Ceramic Filters

Number of Operating Years	5
Number of Production Lines	1
Number of Filters to be Produced	125,000
Total Production Cost	$99,650.95
Unit Cost	$0.80

The total production cost of making 125,000 filters in 5 years is $99,650.95. This yields a cost of $0.80 per ceramic filter.

Activated Carbon Filter

The manufacturing line for making the activated carbon filters consist of a drum burner, hand tools, and various storage tools. A total of four workers are to be hired to work for preparing activated carbon. The following assumptions apply for calculating an estimated cost of making the activated carbon filter level.

- Manufacturing line operates at 8 hours a day, 5 days a week, 50 weeks a year
- A total of 100 activated carbon filters will be produced each day
- A total of 125,000 filters will be produced in 5 years of operation

Coconut shells are to be used to produce activated carbon elements. The number of coconuts required to produce enough carbon for each carbon filter depends on the size of the coconuts. On average, it is assumed that one coconut shell is used to make two carbon filters.

Tables 15 to 17 illustrate the material, equipment, and operating costs required to operate a production line for the activated carbon filters over five years.

Table 15 Material Costs for Running the Activated Carbon Production Line for Five Years

Material	**Cost ($ USD)**	**Remarks**
Coconut shells	18,750.00	Purchased locally at $0.30/coconut
Water	$0.00	Surface water
Total Material Cost	18,750.00	

Table 16 Start-up Equipment Costs for Running the Activated Carbon Production Line

Equipment	**Qty**	**Cost ($ USD)**	**Model**
Drum burner	1	500.00	Custom made
Misc. Tools (Shelves, buckets, hammers)	1	200.00	Tools with basic functionality
Total Equipment Cost		700.00	

Table 17 Operating Cost for Running the Activated Carbon Production Line for One Year

	Qty	**Cost ($ USD)**
Workers	4	$2,720.00
Total Operating Cost		$2,720.00

Table 18 Unit Cost Summary for Production of Activated Carbon Filters

Number of operating years	5
Number of production lines	1
Number of filters to be made	125,000
TOTAL Production Cost	$33,050.00
Unit cost	$0.26

The total production cost of making 125,000 activated carbon filters in 5 years is $33,050.00. This yields a cost of $0.26 per activated carbon filter.

Filter Container

As an alternative to investing in an injection molding machine and fabricating new molds, the filter containers will be outsourced in large batches. The unit cost of a plastic filter container used in this calculation is $0.50.

Total Dual Filter Production Cost

With a $0.80 unit cost for producing a ceramic filter, $0.26 for the activated carbon filter, and $0.50 for the plastic filter container, the total cost of the product adds up to $1.56.

Manufacturing Plant

Manufacturing plant layout for the filter consists of 3 gates, 12 working stations and 8 personnel, shown in Figure 28. Functions for each station and personnel responsibilities are listed in Table 19.

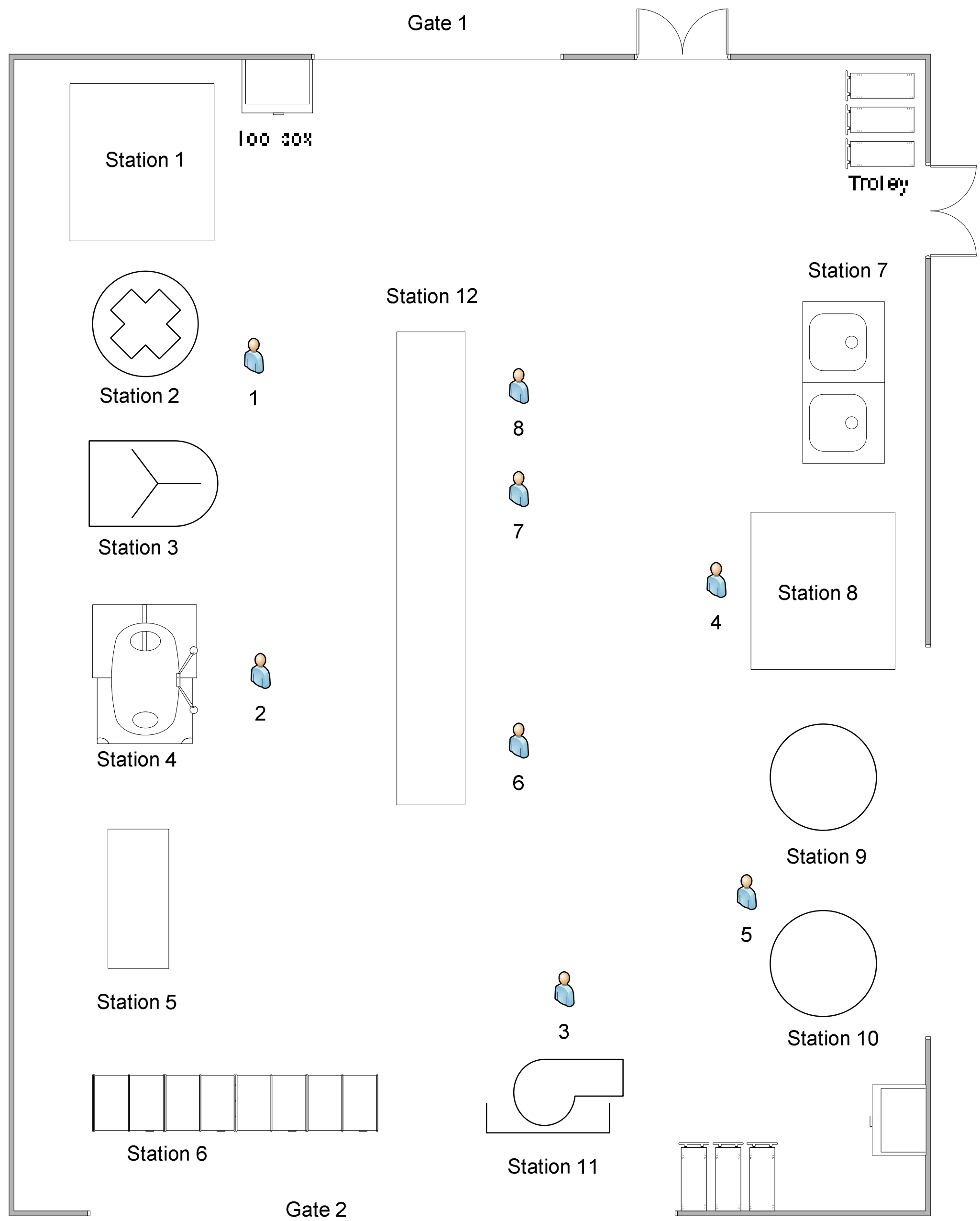

Figure 28 Manufacturing Plant Layout

Table 19 Personnel Responsibilities in the Manufacturing Plant

Station #	Tools	Purpose
1	Hand tools	Crush up clay into pieces
2	Hammer mill	Break down clay into power form
3	Clay mixer	Dry and wet mix of clay and additive
4	Hydraulic press	Form wet clay into pot shape
5	Hand tools	Refining the pot shape
6	Shelf units	Store pot to dry before firing
7	Sink	Washing coconut shells
8	Hand tools	Break down coconut shells into pieces
9	Drum burner	Firing coconut shell
10	Chemical drum	Soaking carbon into solution for activation
11	Kiln	Firing clay pot and activate carbon
12	Working bench	Final assembly
Gate #	**Function**	
1	Transporting raw material and final product	
2	Ventilation, fuel transport	
3	Ventilation, fuel transport	
Personnel	**Responsibility**	
1	Crush and mix up clay mixture	
2	Operating hydraulic press and refining clay pot, then put on shelf to dry	
3	Operating kiln	
4	Clean and crush coconut shells	
5	Fire and soak shells in chemical solution	
6	Crush and measure out activated carbon	
7	Final assembly	
8	Final assembly	

11.0 Difficulties

Various difficulties were encountered throughout the process of building and testing the prototype filters. The relatively slow flow rate was the main concern in the design. This significantly delayed the time for preparing enough water for sample testing. Multiple attempts to improve the performance were carried out, but improvements are small on each try. Moreover, some issued regarding the ceramic filters mixed with what flour occurred during the firing process.

The wheat flour ratio was increased for the second and third batch of the ceramic prototype build. As soon as the mixture ratio reached 40%, the filter element was burnt and cracked in the oven. Figures 29 and 30 illustrate filters that were damaged inside the kiln in the firing process. Cracks were introduced and parts of the filter were chipped off. According to the pottery expert, the entire firing process was forced to halt due to a large amount of smoke coming out of the kiln. Because this was not a normal ceramic material, it was challenging to convince the owner of Little Big Arts School to continue with further firing. Sawdust was used for the remaining batch of prototype filters made.

Figure 28 A Burnt Ceramic Prototype with 40% Wheat Flour Ratio

Figure 29 Damaged Ceramic Prototypes with 40% and 50% Wheat Flour Ratio

There were also delays with the actual modeling of the ceramic filters. Because the availability of machines and tools was limited, all of the ceramic models are molded by hand. With lack of experience in this type of work, it was a challenge to mold the desired shapes, especially with various mixture ratios. At 50% sawdust mixture, the challenge intensified as the material becomes too loose to be molded properly. In the actual manufacturing process, it would be much more efficient if a hydraulic press and a filter mould are in use.

The minimal machinery support was more or less a result of the lack of support from industrial partners. It was promised at the initial stage of the project that full support from the company will be available. If, for any reason, the company cannot provide the support, there will be connections to other firms that can do the job. However, this was not the case when the project commenced - contacting the partner was a frustrating challenge.

12.0 Recommendations

Testing for filter effectiveness should be conducted with the recommended additive, rice husks, as well as with the surface water from different third world countries. Although tolerances were considered in the project, flow rates may differ due difference in water quality. Flow rate testing should be conducted where necessary to achieve maximum flow rate and highest effectiveness.

It is also recommended to apply a coat of silver nitrate solution onto the surface of the ceramic to further reduce bacteria. Since boiling water is the most effective method to disinfect any harmful bacteria and viruses, it is also recommended to boil the water after filtering to insure that the water is safe to drink.

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Appendix A – WHO Safe Drinking Water Guidelines

Table A-1 WHO element/substance guidelines for safe drinking water [40]

Element / substance	Symbol / formula	Amount normally found in water	WHO guideline amount
Aluminum	Al		0.2 mg/l
Ammonia	NH_4	< 0.2 mg/l	No guideline
Antimony	Sb	< 4 µg/l	0.02 mg/l
Arsenic	As		0.01 mg/l
Asbestos			No guideline
Barium	Ba		0.7 mg/l
Beryllium	Be	< 1µg/l	No guideline
Boron	B	< 1mg/l	0.5mg/l
Cadmium	Cd	< 1 µg/l	0.003 mg/l
Chloride	Cl		No guideline
Chromium	Cr^{+3}, Cr^{+6}	< 2 µg/l	0.05 mg/l
Colour			Not mentioned
Copper	Cu		2 mg/l
Cyanide	CN^{-}		0.07 mg/l
Dissolved oxygen	O_2		No guideline
Fluoride	F	< 1.5 mg/l	1.5 mg/l
Hardness	$CaCO_3$ (mg/l)		No guideline
Hydrogen sulphide	H_2S		No guideline
Iron	Fe	0.5 to 50 mg/l	No guideline
Lead	Pb		0.01 mg/l
Manganese	Mn		0.4 mg/l
Mercury	Hg	< 0.5 µg/l	0.006 mg/l
Molybdenum	Mb	< 0.01 mg/l	0.07 mg/l
Nickel	Ni	< 0.02 mg/l	0.07 mg/l
Nitrate & nitrite	NO_3, NO_2		50 mg/l and 3mg/l
Turbidity			Not mentioned
pH			No guideline
Selenium	Se	< 0.01 mg/l	0.01 mg/l
Silver	Ag	5 to 50 µg/l	No guideline
Sodium	Na	< 20mg/l	No guideline
Sulphate	SO_4		No guideline
Tin	Sn		Not mentioned
TDS			No guideline
Uranium	U		0.015 mg/l
Zinc	Zn		No guideline

Table A2 WHO organic compound guidelines for safe drinking water [40]

Group	Substance	Formula	WHO guideline amount
Chlorinated alkanes	Carbon tetrachloride	CCl_4	4 µg/l
	Dichloromethane	CH_2Cl_2	20 µg/l
	1,1-Dichloroethane	$C_2H_4Cl_2$	No guideline
	1,2-Dichloroethane	$ClCH_2Ch_2Cl$	30 µg/l
	1,1,1-Trichloroethane	CH_3CCl_3	No guideline
Chlorinated ethenes	1,1-Dichloroethene	$C_2H_2Cl_2$	No guideline
	1,2-Dichloroethene	$C_2H_2Cl_2$	50 µg/l
	Trichloroethene	C_2HCl_3	20 µg/l
	Tetrachloroethene	C_2Cl_4	40 µg/l
Aromatic hydrocarbons	Benzene	C_6H_6	10 µg/l
	Toluene	C_7H_8	700 µg/l
	Xylenes	C_8H_{10}	500 µg/l
	Ethylbenzene	C_8H_{10}	300 µg/l
	Styrene	C_8H_8	20 µg/l
	PAH	$C_2H_3N_1O_5P_{1\ 3}$	Not mentioned
Chlorinated benzenes	Monochlorobenzene	C_6H_5Cl	No guideline
	1,2-Dichlorobenzene	$C_6H_4Cl_2$	1000 µg/l
	1,3-Dichlorobenzene	$C_6H_4Cl_2$	No guideline
	1,4-Dichlorobenzene	$C_6H_4Cl_2$	300 µg/l
	Trichlorobenzene	$C_6H_3Cl_3$	No guideline
Miscellaneous organic constituents	Di(2-ethylhexyl)adipate	$C_{22}H_42O_4$	No guideline
	Di(2-ethylhexyl)phthalate	$C_{24}H_{38}O_4$	8 µg/l
	Acrylamide	C_3H_5NO	0.5 µg/l
	Epichlorohydrin	C_3H_5ClO	0.4 µg/l
	Hexachlorobutadiene	C_4Cl_6	0.6 µg/l
	Ethylenediaminetetraacetic acid	$C_{10}H_{12}N_2O_8$	600 µg/l
	Nitrilotriacetic acid	$N(CH_2COOH)_3$	200 µg/l
	Dialkyltins	R_2SnX_2	No guideline
	Tributyltin oxide	$C_{24}H_{54}OSn_2$	No guideline

Table A3 WHO disinfectant and disinfectant by-products guideline for safe drinking water [40]

Group	Substance	Formula	WHO guideline amount
Disinfectants	Chloramines	NH_2Cl	Not mentioned
	Chlorine	Cl_2	5 mg/l
	Chlorine dioxide	ClO_2	No guideline
	Iodine	I_2	No guideline
Disinfectant by-products	Bromate	BrO_3^-	10 µg/l
	Chlorate	ClO_3^-	70 µg/l
	Chlorite	ClO_2^-	70 µg/l
	2-Chlorophenol	C_6H_5ClO	No guideline
	2,4-Dichlorophenol	$C_6H_4Cl_2O$	No guideline
	2,4,6-Trichlorophenol	$C_6H_3Cl_3O$	200 µg/l
	Formaldehyde	HCHO	No guideline
	MX	$C_5H_3Cl_3O_3$	No guideline
	Bromoform	$CHBr_3$	100 µg/l
	Dibromochloromethane	$CHBr_2Cl$	100 µg/l
	Bromodichloromethane	$CHBrCl_2$	60 µg/l
	Chloroform	$CHCl_3$	300 µg/l
	Monochloroacetic acid	$C_2H_3ClO_2$	No guideline
	Dichloroacetic acid	$C_2H_2Cl_2O_2$	50 µg/l
	Trichloroacetic acid	$C_2HCl_3O_2$	20 µg/l
	Chloral hydrate	$CCl_3CH(OH)_2$	No guideline
	Chloroacetones	C_3H_5OCl	No guideline
	Dichloroacetonitrile	C_2HCl_2N	20 µg/l
	Dibromoacetonitrile	C_2HBr_2N	70 µg/l
	Bromochloroacetonitrile	$CHCl_2CN$	No guideline
	Trichloroacetonitrile	C_2Cl_3N	No guideline
	Cyanogen chloride	ClCN	70 µg/l
	Chloropicrin	CCl_3No_2	No guideline

Table A4 WHO pesticides guideline for safe drinking water [40]

Substance	Formula	WHO guideline amount
Alachlor	$C_{14}H_{20}ClNO_2$	20 µg/l
Aldicarb	$C_7H_{14}N_2O_4S$	10 µg/l
Aldrin and Dieldrin	$C_{12}H_8Cl_6$ and $C_{12}H_8Cl_6O$	0.03 µg/l
Atrazine	$C_8H_{14}ClN_5$	2 µg/l
Bentazone	$C_{10}H_{12}N_2O_3S$	No guideline
Carbofuran	$C_{12}H_{15}NO_3$	7 µg/l
Chlorotoluron	$C_{10}H_{13}ClN_2O$	0.2 µg/l
DDT	$C_{14}H_9Cl_5$	30 µg/l
1,2-Dibromo-3-chloropropane	$C_3H_5Br_2Cl$	1 µg/l
2,4-dichlorophenoxyacetic acid	$C_8H_6Cl_2O_3$	1 µg/l
1,2-dichloropropane	$C_3H_6Cl_2$	30 µg/l
1,3-dichloropropane	$C_3H_6Cl_2$	40 µg/l
1,3-dichloropropene	$CH_3CHClCH_2Cl$	No guideline
Ethylene dibromide	$BrCH_2CH_2Br$	20 µg/l
Heptachlor and heptachlor epoxide	$C_{10}H_5Cl_7$	Not mentioned
Hexachlorobenzene	$C_{10}H_5Cl_7O$	No guideline
Isoproturon	$C_{12}H_{18}N_2O$	9 µg/l
Lindane	$C_6H_6Cl_6$	2 µg/l
MCPA	$C_9H_9ClO_3$	2 µg/l
Methoxychlor	$(C_6H_4OCH_3)_2CHCCl_3$	20 µg/l
Metolachlor	$C_{15}H_{22}ClNO_2$	10 µg/l
Molinate	$C_9H_{17}NOS$	6 µg/l
Pendimethalin	$C_{13}H_{19}O_4N_3$	20 µg/l
Pentachlorophenol	C_6HCl_5O	9 µg/l
Permethrin	$C_{21}H_{20}Cl_2O_3$	300 µg/l
Propanil	$C_9H_9Cl_2NO$	No guideline
Pyridate	$C_{19}H_{23}ClN_2O_2S$	No guideline
Simazine	$C_7H_{12}ClN_5$	2 µg/l
Trifluralin	$C_{13}H_{16}F_3N_3O_4$	90 µg/l

Appendix B – Water Filter Flow Rate Calculation

Flow rate through the side walls of the ceramic filter will be neglected, as the value is small compared to flow rate through the bottom wall. Any flow through the side wall will only increase the flow rate with reference to the calculated value.

Assumptions made

1. water consumption 2L/capita/day
Volume required: V = volume [m^3] = 2L × 8 people = 16L/day = 0.016 m^3/day
2. operating condition: standard temperature and pressure
3. filtration duration: 8 hr/day
4. flow through activated carbon elements are faster than ceramic, and since ceramic is the restricting factor, only calculation for ceramic filter is carried out

Known values

V = volume = 0.016 m^3
k = permeability = 1×10^{-13} m^2
ρ = density = 1000 kg/m^3
μ = viscosity = 0.001 Pa·s

Flow rate calculation

Volumetric flow rate required: *Q = flow rate [m^3/s]*

$$t = \frac{V}{Q} \Rightarrow Q = \frac{V}{t} = \frac{0.016\, m^3}{8\, s} = 0.002\, m^3/hr$$

Variables to optimize

w = filter wall thickness [m]
h = height of filter [m]
r = radius of filter [m]

$$Q = v \times A$$

$$v = \frac{k \times \Delta P}{\mu w}$$

$$\Delta \mathrm{P} = \rho \mathrm{gh}$$

$$A = \pi r^2$$

$$\therefore Q = \frac{k \times \pi r^2 \times \rho g h}{\mu w}$$

The dimensions of the ceramic filter in the final design are w = 0.010m, h = 0.200m and r = 0.125m. Therefore, a flow rate of Q = 0.003 m^3 per hour or 83 liters per day can be achieved. This is a reasonable value for a home use filter. Comparing to the required flow rate calculation, the projected flow rate gives a 50% tolerance for any unaccounted factors.

Appendix C – Economic Analysis Calculations

Ceramic Filter

Materials Cost

- Clay to be purchased locally at approximately $0.06 USD/brick
- 125,000 bricks required to produce 125,000 ceramic filters in 5 years
- Rice husks to be purchased from India at approximately $500 USD for sufficient supplies to produce 125,000 filters

The materials cost needed to manufacture 125,000 ceramic filters is estimated as below.

$$Cost_{material} = 125{,}000 \times \$0.06 + \$500 = \$8{,}000.00$$

Equipments cost

- Clay crusher $10.00
- Meadow #5 hammer mill $1,680.00
- Bailey clay mixer $4,082
- Misc. Tools $200.00
- Draper hydraulic press with mould $542.85
- L&L kiln $5,950

$$Cost_{equipment} = \$10 + \$1680 + \$4082 + \$200 + \$542.85 + \$5950 = \$12464.85$$

Operating Costs

$$Cost_{Operating} = Cost_{labour} + Cost_{power}$$

Labour cost in one year

- 4 workers working for the ceramic filters
- Gross national income per capita in Kenya: $680 USD/year

$$Cost_{labour} = 4 \times \$680 = \$2{,}720.00$$

Power cost

- Hammer mill: 10kW
- Clay mixer: 4.584kW
- Kiln: 19.935kW
- Operating hours in one year: 2000

- Cost of electricity in Kenya: $0.19 USD/kWh

$P_{hammer\ mill} = 10 \times 2000 = 20000kWh$

$P_{clay\ mixer} = 4.584 \times 2000 = 9168kWh$

$P_{kiln} = 19.935 \times 2000 = 39870kWh$

$P_{electricity} = P_{hammer\ mill} + P_{hammer\ mill} + P_{hammer\ mill} = 69038kWh$

$Cost_{power} = \$0.19 \times 69{,}038 = \$13{,}117.22$

$\therefore Cost_{Operating} = Cost_{labour} + Cost_{electricity} = \$2{,}720 + \$13117.22 = \$15837.22$

Production cost

- 5 operating years
- Number of filters to produce: 125,000
- Number of production line: 1

$Cost_{Production} = Cost_{materials} + Cost_{equipments} + Cost_{operating} \times Operating\ years$

$Cost_{Production} = \$8000 + \$12464.85 + \$15837.22 \times 5year = \$99650.95$

$Unit\ Cost_{Ceramic} = Cost_{Production} \div Number\ of\ filters = \$99650.95 \div 125000 = \$0.80$

Activated Carbon Filter

Materials Cost

- Coconut shells to be purchased locally at approximately $0.30 USD each
- Depending on sizes of shells, approximately 62,500 shells are needed to produce 125,000 activated carbon filters in 5 years
-

The material cost associated with manufacturing 125000 activated carbon filters is:

$Cost_{materials} = \$0.30 \times 62{,}500 = \ \$18750.00$

Equipment cost

- Metal drum burner to be custom made locally
- Approximated drum burner cost: $500.00 USD
- Misc. tools: $200.00 USD

$Cost_{equipments} = \$500 + \$200 \ = \ \$700.00$

Operating Costs

Labour cost in one year

- 4 workers working for the activated carbon filters
- Gross national income per capita in Kenya: $680 USD/year

$Cost_{Operating} = Cost_{labour} = 4\ workers \times \$680 = \$2{,}720.00$

Production cost

- 5 operating years
- Number of filters to produce: 125,000
- Number of production lines: 1

$Cost_{Production} = Cost_{materials} + Cost_{equipments} + Cost_{operating} \times Operating\ years$

$Cost_{Production} = \$18{,}750 + \$700 + \$2{,}720 \times 5year = \$33{,}050.00$

$Unit\ Cost_{Carbon} = Cost_{Production} \div Number\ of\ filters = \$33{,}050.00 \div 125{,}000 = \$0.26$

Filter Container

Plastic filter containers are to be outsourced in large batches. The unit cost of a plastic filter container used in this calculation is $0.50.

$Unit\ Cost_{container} = \$0.50$

Total Dual Filter Production Cost

$Unit\ Cost_{TOTAL} = Unit\ Cost_{ceramic} + Unit\ Cost_{carbon} + Unit\ Cost_{container}$

$= \$0.80 + \$0.26 + \$0.50 = \$1.56$