12-2019

Biochar as a means of Water Purification in Haiti

Caolan Keenan
Grand Valley State University

Honors Senior Project

Biochar as a means of Water Purification in Haiti

Caolan Keenan and Peter Wampler. Grand Valley State University, 2019.

Abstract

Our research set out to determine if biochar, a compound made by burning organic plant matter in a low oxygen environment, would remove *E. coli* from contaminated water collected from the Grand River in Allendale, MI. Simple materials were used to construct a filter so that a similar filter could be constructed and used in Haiti. Previous research has shown biochar to be effective at trapping bacteria and other contaminants in the porous surface and by binding other non organic contaminants. We constructed multiple filters using PVC pipe, gravel, sand, and biochar and ran three experiments with different amounts of biochar and filtration procedures. Water collected after passing through filters was tested using the IDEXX method to determine bacterial counts. Our research showed that the biochar was effective at removing *E. coli,* removing 88.7 to 100 % of the E. coli in the source water. The amount of biochar present in the filter appears correlate with filter effectiveness.. Future research is needed to identify which sand and charcoal combinations and flow rates result in the most effective E. coli removal.

Background

Haiti is facing a water crisis, as the country in the Western Hemisphere with the lowest access to clean drinking water[1], solutions that are easily implemented and sustainable as well as effective are necessary for the Haitian people. Biochar has shown potential as a means of removal of contaminants from water using its porous surface to trap potentially harmful materials and deliver clean drinkable water. It is a renewable, cheap, and low emission method to purify water. It does not result in harmful byproducts[2] found in other methods like chlorination or have the expense and limitations of other water technologies. Production of biochar is done by pyrolysis, the process of burning wood with under hypoxic conditions, which can be done by burying a burning pile of wood. Biochar works by adsorption, a process in which particles of a matter are trapped on the surface of the adsorbent, in our case biochar. The biochar granules grab onto the bacteria and chemical contaminants found in dirty water and form a film around the granule, made up of the particles it has trapped. The nanopores found in the biochar serve to increase the surface area, part of why it is an effective means to filtration. These pores lead to increased "trapping" of contaminants, leading to cleaner water[3]. Research has been done on biochar to test the effectiveness of its adsorption to remove contaminants from water, but our research focuses specifically on creating a filter using sand, gravel, and biochar to remove *E. coli,* an effective tracer for water contaminated with human and animal waste. A study done in 2014 at Stanford University[4] found biochar to be 3 times more effective at removing *E. coli* from stormwater runoff when compared to pure sand filters, and they

[1] Gelting, R., Bliss, K., Patrick, M., Lockhart, G., & Handzel, T. (2013). Water, Sanitation and Hygiene in Haiti: Past, Present, and Future. The American Journal of Tropical Medicine and Hygiene, 89(4), 665–670. https://doi.org/10.4269/ajtmh.13-0217

[2] Gwenzi, W., Chaukura, N., Noubactep, C., & Mukome, F. N. D. (2017). Biochar-based water treatment systems as a potential low-cost and sustainable technology for clean water provision. *Journal of Environmental Management*, *197*, 732–749. https://doi.org/10.1016/j.jenvman.2017.03.087

[3] PROFILE: USING BIOCHAR FOR WATER FILTRATION IN RURAL SOUTH EAST ASIA. (2018, April 4). Retrieved November 29, 2019, from Biochar-international website: https://biochar-international.org/water_filtration/

[4] Mohanty, S. K., Cantrell, K. B., Nelson, K. L., & Boehm, A. B. (2014). Efficacy of biochar to remove Escherichia coli from stormwater under steady and intermittent flow. *Water Research*, *61*, 288–296. https://doi.org/10.1016/j.watres.2014.05.026

further found that it held onto these trapped bacteria better than sand when water was reintroduced to the filter. This study found that a 30% biochar/70% iron laiden sand filter was able to remove 97% of *E. coli* from contaminated water. A follow up study done in Minnesota in 2018 found biochar to be an effective means of removing over 72%[5] of *E. coli* from stormwater runoff and bodies of water in Minnesota.

Potential areas of concern for biochar as a filter is that this film around the granules can accumulate and take up all the available active sites for adsorption. This effect can be diminished by adding sand and gravel to a filter to remove some of the larger particles in the water before they reach the biochar, and as such we decided to place both sand and gravel above the biochar in our filters in an effort to extend their viability.

Materials

Materials for this research were chosen based on their availability in Haiti The goal was to choose methods and materials that can be implemented using resources found in rural areas that these filters would be used. Biochar in the form of charcoal (Chabon) is widely used as a fuel in Haiti and can be obtained easily. Sand and gravel are also abundant and the filter housing could be made from clay or wood. We used PVC and other materials not available in Haiti in order to reduce the potential for contamination, as it is easily sanitized (Table 1). Future experiments will be run using clay or wood vessels to determine the best methods for construction and use.

Table 1. Materials used for experimental setup.

• 2” PVC Piping • 2’ clear hose • Stands • 100mL sample bottles • 2 graduated cylinders • Zip ties • Full Circle Hardwood Lump Charcoal	• KolorScape washed play sand • SlapChop (for crushing charcoal) • Incubator • Quanti-Tray 2000 Sealer (Mo. 2X, IDEXX) • Colilert 2000 • UV Light

[5] Innovative Filter Design Application Targeting E. Coli and Phosphorus Removal. (2018, December 21). Retrieved December 10, 2019, from Stormwater Online website: https://www.stormwateronline.com/home/article/13035719/innovative-filter-design-application-targeting-e-coli-and-phosphorus-removal

• Vigoro Pea Pebbles • Spicket • Landscaping fabric	• 100 well Quanti-Tray • 2” PVC cap • Silicone • Cheesecloth

Methods

The setup used in this experiment was a 2” diameter PVC pipe with a cap on the bottom. The cap contained a nozzle extruding at a 90-degree angle outwards. All fittings were secured using silicone to prevent leaks, and to seal and bond the materials. Layers of sand, gravel, and charcoal were separated by cheesecloth cut to fit within the PVC pipe (see Figure 1). Below all materials in the PVC was a piece of landscaping fabric cut to size used to retain any of the filtering materials from the filtered water. The setup consisted of four of these constructed filters attached to a 2-foot long piece of clear plastic tubing via the nozzle running into a collecting vessel. The filters were held up on stands using zip ties.

Our research was focused on assessing if biochar is a reasonable filtration method for removing *E. coli* from contaminated water, while using other materials such as sand and gravel to help both flow rate and removal of larger contaminants. First, we collected data on the contamination of various water sources around campus without filtration. Once we established a good source of water with *E. coli*, bacterial die off was assessed by taking a sample, then leaving it in refrigeration for one week, testing samples at determined intervals. We then made our filters. In order to determine if our filters were effective, and if the results were consistent between the four setups, we ran four identical filters with constant amounts of each material within them. In order to assess the impact of allowing water to remain in the filter two filters were kept with water in them for one week, and two were allowed to drain and dry out. The third set of experiments was to test whether the amount of biochar would correlate with bacteria removal. Three filters were constructed with varying amounts of biochar, and one filter was created with no biochar to ensure that it was, in fact, the biochar removing the bacteria from the water.

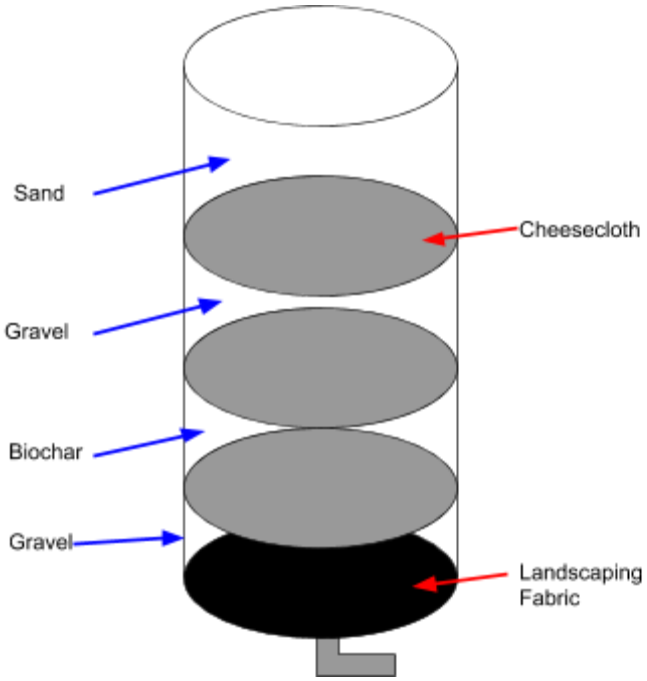

Figure 1. A rough sketch of the setup within the filter showing the layers and arrangement of the materials.

E. coli was measured in samples collected from the filters and water sources using the IDEXX method. This test takes a 100 mL sample put into a QuantiTray 2000, which is a tray divided into 97 wells, 49 “large” and 48 “small.” The 100 mL water sample is mixed with a growth medium to encourage bacterial growth and then poured into the tray, which is sealed and then incubated at 35 °C for 18-24 hours. Upon removal, positive cells are counted, coliform positive cells are indicated by yellowing of the cell, and *E. coli* positive cells are indicated by glowing cells under a blacklight. Using an IDEXX table for the tray, the amount of positive cells translate to a “Most Probable Number” (MPN) value, which has a 95% confidence interval for quantifying the amount of bacteria in the sample.


Figure 2. Setup of the filter with hose leading to collecting vessel.

Preliminary Experiment

To assess the bacterial population in various water sources, we ran contaminated water collected from the Grand River, Zumberg Pond, Calder Creek, and deionized (DI) water through a colilert test. 100 ml samples were mixed with media to culture bacteria, poured into a Quanti-Tray, sealed, and then incubated at 35 °C for 18-24 hours. After removal the Coliform positive wells (yellow) were counted, then they were put under a blacklight to assess *E. coli* and positive wells were counted (blue). Counts were then assessed using the MPN chart and given a value to determine contamination.

Samples taken from the Grand River were tested daily to assess bacterial die-off. One large sample was taken and the collecting vessel stayed in a fridge for 1 week. Samples were taken from this initial sample at 4, 5, 6, and 7 days. All were mixed with media and placed in a tray then incubated for one day, then assessed to determine bacterial counts.

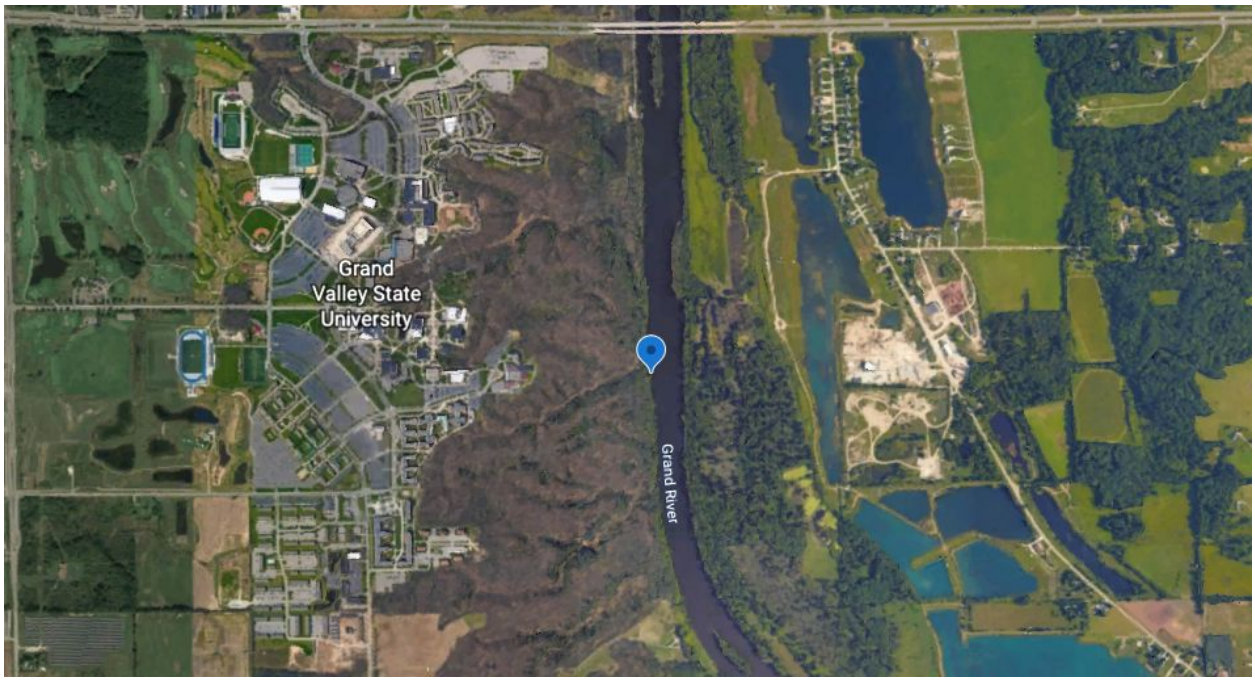

Figure 3. Location of water sample collection from Grand River.

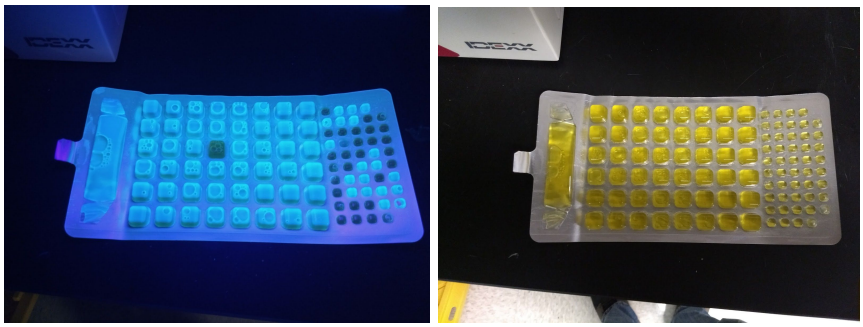

Figure 4&5. The left image shows the *E. coli* test of the Quanti-Tray 2000 under blacklight, positive cells are indicated by the green glow. The right image shows positive coliform cells, indicated by the yellowing of a cell. This sample was a raw GR water sample, thus the high positive count.

Experiment 1

All materials were weighed to achieve four identical filters. E. coli was measured in water samples before and after passing through the filters (Table 2). Blank Deionized (DI) water was run and unfiltered Grand River (raw) were also run for comparison and background. The initial run consisted of 1L of DI water plus an additional 100 mL of DI water. A 100 mL

sample was collected. 6cm of head (measured from the top of PVC) was maintained on all tubes until all the water passed through the filter.

Table 2. Material masses for identical filter units.

Materials (g)	Filter 1	Filter 2	Filter 3	Filter 4
Sand	801.3	800.4	801.4	799.0
Top Gravel	200.6	200.5	200.1	200.8
Biochar	30.6	30.5	30.3	30.5
Bottom Gravel	201.1	201.4	201.0	201.5

After passing the DI water a 600mL of raw Grand River (GR) water was passed through each filter in the order of 4, 3, 2, 1. A 100mL sample was taken of the effluent during the last 200mL passing through the filter. Colilert media was mixed with the water sample until no solids were present, then the sampler was put in a tray and sealed. Samples were incubated at 35C for 18-24 hours in a small incubator oven. The next day trays were removed and positive cells were counted then converted to an MPN value.

Outlet tubes for filters 1 and 2 were elevated so that water would remain in them for one week to assess how well the filters worked after remaining wet and if bacteria cultured within them. They were filled to the 6 cm head mark, and the plastic tube was elevated above the top of the filter. They were then sealed to prevent contamination. Tubes 3 and 4 were drained and then sealed to prevent any contamination between tests.

Experiment 2

Filters 1 and 2 were left with the water from the previous week were filled up to the 6cm mark used to maintain the head. The remaining water was drained before pouring new water into them. New GR water was collected and 600 mL was put through each filter, with a 100 ml sample collected in the last 200 ml. The order of tests was 4,3,2,1. Two raw GR samples and blank DI water were also incubated and tested.

Experiment 3

Filters 1,2,3 were taken apart and sanitized. New filters were constructed with varying amounts of biochar present in each (Table 3.). Filter 4 was left unchanged from the previous setup.

Table 3. Filter setups for testing different biochar amounts.

Materials (g)	Filter 1	Filter 2	Filter 3	Filter 4
Sand	800.4	800.3	800.2	799.0
Top Gravel	none	200.0	200.2	200.8
Biochar	none	60.0	120.1	30.5
Bottom Gravel	200.2	200.0	200.2	201.5

600 mL of DI water was run through all 4 filters before passing the GR water. 600 mL of fresh GR water was put through each filter as before, and a 100mL sample was taken in the last 200mL of flow. Each sample was analyzed for coliform and *E. coli* bacteria using the IDEXX colilert method..Results

Results were determined by an MPN value gathered from the count of positive *E. coli* cells after incubation at 35 degrees Celsius. Our research aimed at lowering the *E. coli* count within our samples since this is the primary harmful contaminant in Haitian water, thus the efficacy of results was determined by a significant decrease in the number of *E. coli* cells. Coliform levels were recorded in some experiments, but are not particularly relevant as Coliform itself does not pose a threat to human health, but can be indicative of the presence of other harmful contaminants.

Results

Preliminary Experiment

Table 4. Results showing the bacterial population in samples from Grand River, Calder Creek, Zumberg Pond, and blank DI water. Bacterial die-off is shown at the bottom of the table, with samples that were left in refrigeration for 4, 5, 6, and 7 days then incubated.

Sample ID	Sample Date	Analyte	QT/2000 Lg Wells	QT/2000 Sm Wells	MPN
GR #1	09/03/2019	Coliforms	49	48	> 2419.6
GR #2	09/03/2019	Coliforms	49	47	2419.6
GR #3	09/03/2019	Coliforms	49	25	461.1
Calder_Creek	09/03/2019	Coliforms	49	48	> 2419.6
Zumberg	09/03/2019	Coliforms	49	42	1299.7
BLANK	09/03/2019	Coliforms	0	0	< 1.0
Grand River #1	09/03/2019	E. coli	40	4	83.3
Grand River #2	09/03/2019	E. coli	39	1	72.2
Grand River #3	09/03/2019	E. coli	40	7	90.8
Calder_Creek	09/03/2019	E. coli	49	46	1986.3
Zumberg	09/03/2019	E. coli	0	0	< 1.0
BLANK	09/03/2019	E. coli	0	0	< 1.0
GR 4 day	09/20/2019	E. coli	25	3	37.9
GR 5 day	09/20/2019	E. coli	22	4	33.6
GR 6 day	09/20/2019	E. coli	13	0	14.8
GR 7 day	09/20/2019	E. coli	9	0	9.8

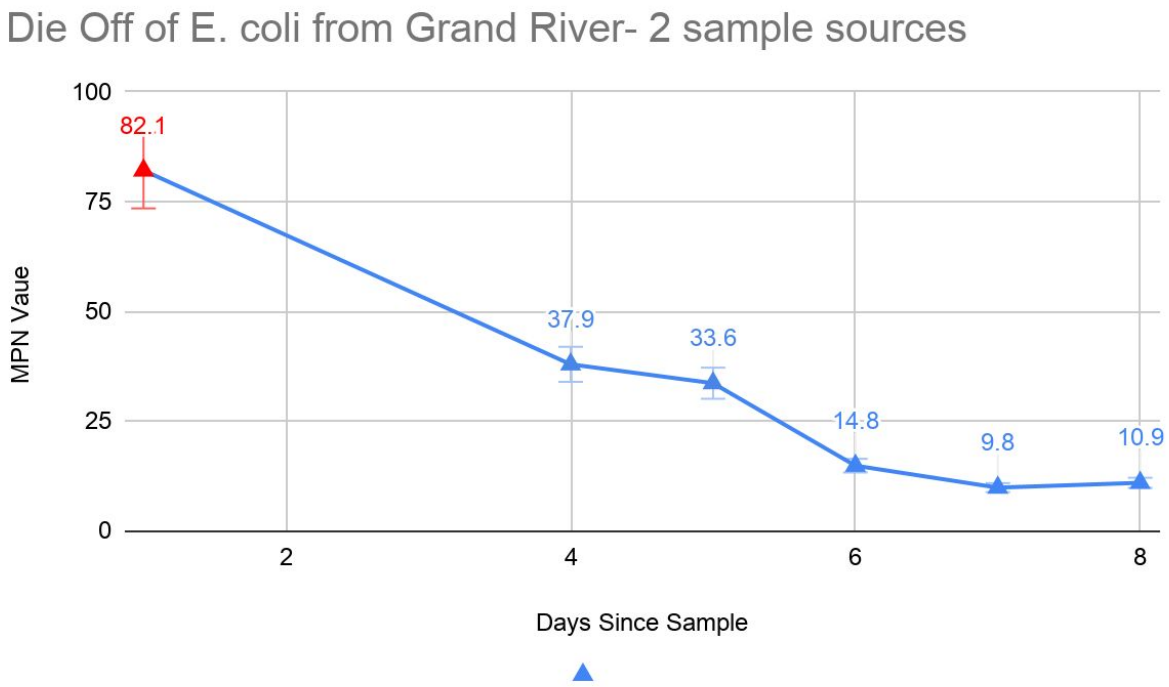

Figure 6. Bacterial population of the Grand River Sample taken on 9/20/2019 (blue) and 9/3/2019 (red). The initial sample on 9/3 was collected and tested the day after, while the 9/20 sample was left in refrigeration for three days before taking a sample out and then incubating for one day. Standard deviation of the first sample obtained by averaging the three values from the three samples (82.1), with a deviation of 10.53%. The 9/3 sample consisted of 3 samples, which we averaged to 82.1 (83.3,72.2,90.8).

The preliminary testing allowed us to identify the various bacterial populations in water sources from around campus. From these sources, the Grand River was shown to be continuously contaminated and contained ample bacteria from which to test the efficacy of our filter. Due to the rapid die-off of bacterial samples shown above (Table 1 and Figure 6), we deemed it necessary to collect a new sample of water from the Grand River with every round of testing in order to identify the removal rate of filters.

Experiment 1

Initial flow observations: Initial DI water coming out of filters was slightly murky, likely due to the sand, as the water was a pale yellow color. However, it became clear after a few minutes of flow.

Experiment 1 consisted of pouring 1,100mL of DI water through all filters, with a 100mL collection in the last 400mL. This was done to flush out any potential contaminants within the filter, as well as to detect if bacteria were already present in the filter. 6 cm of head was maintained on all filters through pouring.

Table 5. Results show a significant decrease in the counts of both coliforms and *E. coli* indicating some removal within the filter testing for the presence of *E. coli.*

Sample ID	Sample Date	Analyte	Lg Wells	Sm Wells	MPN	% Reduction
Grand River Raw	10/17/2019	E. coli	49	40	1119.9	N/A
Blank#1 - DI Water	10/17/2019	E. coli	0	0	0	N/A
Blank#2 - DI Water	10/17/2019	E. coli	0	0	0	N/A
Blank#3 - DI Water	10/17/2019	E. coli	0	0	0	N/A
Blank#4 - DI Water	10/17/2019	E. coli	1	0	1	N/A
Filtered #1	10/17/2019	E. coli	28	4	45.7	95.9
Filtered #2	10/17/2019	E. coli	17	2	22.8	98
Filtered #3	10/17/2019	E. coli	26	2	38.4	96.6
Filtered #4	10/17/2019	E. coli	30	3	48.7	95.7

E. coli in GR water was reduced and we calculated a reduction value (100- 100 X (filtered MPN/raw MPN)) after running through all filters, total coliforms were reduced by a factor of around 610. This shows that the filters were very effective at lowering the counts of bacteria in the samples, although 100% removal was not seen. Further, the negatives found in the blank DI samples shows that filters were not contaminated beforehand, giving good evidence that the filtering of GR water was efficient, but not completely successful, excluding the water poured through filter 4, which had one positive large cell. This does not affect the data as this could have been contaminated in the transfer of water from the vessel to the filter, or from the filter to the trays. Results indicate that the filters are removing bacteria, but the broad range of results shows variance in efficacy, which could be due to differing flow rates (affecting contact time with biochar), the size of biochar particles, or the actual amount of biochar, although the masses of biochar were the same throughout the filters. We also decided to test if leaving water in the filters would increase bacteria removal on the next use, so the filters 1&2 were left with water for one week.

Experiment 2

Initial flow observations: On draining the standing water from filter 1&2, filter 1 had slightly less than 200 mL on draining and appeared very milky. Filter 2 had 450 mL in it and was slightly clearer than filter 1. The discrepancy between the amount of water was difficult to interpret, as we filled both filters up to the same line and made sure that the water in the drainage tube was level with the water level in the filter.

Table 6. Comparisons between the bacteria removal of the "wet" filters (1&2), and the "dry" filters (3&4) as well as the levels of bacteria in the raw GR water and blank DI water.

Sample #	Description	Large_wells	Small_wells	E_Coli MPN	Large_wells	Small_wells	Coliform MPN
1025201901	Raw GR Water #1	49	20	344.8	49	44	1553.1
1025201902	Raw GR Water #2	49	18	307.6	49	45	1732.9
1025201903	Filter #1	26	1	36.9	49	11	214.3
1025201904	Filter #2	22	1	29.5	49	16	275.5
1025201905	Filter #3	22	0	28.2	48	12	193.5
1025201906	Filter #4	16	1	20.1	48	27	378.4
1025201907	Blank	0	0	< 1	0	0	< 1

The effect of leaving water standing in filters did not seem to have a positive effect on bacterial removal and seemed to actually be slightly less effective than the filters that were drained. However, when comparing the results of these filters to the initial experiment 1, filters 1,3, and 4 removed more bacteria on the second round of use. This finding could potentially suggest an "activation factor" of the filters, where the initial use of the filter with dirty water does not clean as well as the second or third runs. Filter 2 saw an increase in the MPN value by a 6.7 and 5 more large wells, but 1 fewer small wells than filter 2 in experiment 1. This could be due to a variety of factors, and reasons for this finding are not clear, although the difference is not immensely significant. Further differences are found in the water source, the raw Grand River MPN value in experiment 1 was 1119.9, whereas the MPN for the raw water was 307.6 and 344.8, which is substantially lower than the first sample collection. This could lead to the smaller MPN values found after filtration in this experiment, as there was less bacteria to remove to begin with. A blank DI sample was run through and showed 0 contamination, still indicating that the adhesion of previously removed contaminants to biochar is strong and do not contaminate clean water.

Experiment 3

Initial flow observations:

Filter 1- The initial water collected in the graduated cylinder was very silty and murky with lots of sand in it. Likely due to no extra barriers that were provided in the other filters.

Filter 2- Initially the water collected was murky, although less so than filter 1. Slow flow rate at the beginning that gradually increased after use.

Filter 3- Initial water collected in cylinder was very black and dark, likely due to the increased charcoal in the filter. Also very slow to drain.

Table 7. Results from the third experiment testing the effects of varying amounts of charcoal, the amount of charcoal in grams is listed in the "Charcoal" column. Well counts are shown for both *E. coli* and coliform. Coliform data is listed as well for comparison of removal of bacteria other than *E. coli*.

Sample#	Description	Charcoal (g)	Large_wells	Small_wells	E_Coli	Large_wells	Small_wells	Coliform
1105201901	Raw GR Water #1	None	48	17	238.2	49	46	1986.3
1105201902	Raw GR Water #2	None	45	18	172.6	49	46	1986.3
1105201903	Filtered DI Water Filter #1	None	0	0	< 1	0	0	< 1
1105201904	Filtered GR Water Filter #1	None	6	0	6.3	26	1	36.9
1105201905	Filtered DI Water Filter #2	60	0	0	< 1	28	0	39.5
1105201906	Filtered GR Water Filter #2	60	5	0	5.2	41	4	88
1105201907	Filtered DI Water Filter #3	120	0	0	< 1	0	0	< 1
1105201908	Filtered GR Water Filter #3	120	0	0	< 1	1	0	1
1105201909	Filtered DI Water Filter #4	30	0	0	< 1	49	48	>2419.6
1105201910	Filtered GR Water Filter #4	30	8	1	9.7	49	48	>2419.6

Experiment 3 provided excellent data for the effect of the amount of charcoal within a filter and the bacteria removal efficacy. As the amount of charcoal increased the removal of *E. coli* also increased, and thus we saw a lowered MPN value. The most exciting finding was that fact that filter 3, which had the most charcoal (120 g.) had a 100% removal rate of *E. coli,* and only had a single positive large well for coliform. However, the two raw GR samples had lower MPN values before even being filtered than any of the other raw samples in previous experiments. This was a difficult variable to control as the collection of water was dependant on the river conditions, and with rising water levels we concluded that the water bacteria was diluted by all the runoff and rain in the area. However, the results still bode well for the promise of removal, and we saw significant decreases in bacterial contamination in all the filters. When comparing to the sand filter, the ones containing biochar were more effective at removing *E. coli* than the sand/gravel filter, indicating that the biochar is the active material and does itself remove bacteria. The lack of bacteria in the

DI water runs shows that the bacteria are not culturing in the filters, and that the biochar adhesion to contaminants is effective at preventing contamination of water poured through after pouring a dirty sample through. These results would need to be repeated, hopefully with a more contaminated GR sample in order to discover the true efficacy of the biochar vs. sand and if our 120g charcoal filter still removed all of the bacteria.

Summary Data

Experiment #/Filter #	Charcoal	E. coli input MPN	E. coli filtered MPN	% change
1/1	30g ("dry")	1119.9	45.7	-95.92%
1/2	30g ("dry")	1119.9	22.8	-97.96%
1/3	30g ("dry")	1119.9	38.4	-96.57%
1/4	30g ("dry")	1119.9	48.7	-95.65%
2/1	30g ("wet")	326.2	36.9	-88.69%
2/2	30g("wet")	326.2	29.5	-90.96%
2/3	30g ("dry")	326.2	28.2	-91.35%
2/4	30g ("dry")	326.2	20.1	-93.84%
3/1	None	205.4	6.3	-96.93%
3/2	60g	205.4	5.2	-97.47%
3/3	120g	205.4	0	-100.00%
3/4	30g	205.4	9.7	-95.28%

Table 8. Shows all filters in all three experiments, listed is the *E. coli* levels in the GR water sample taken (input) and the resulting MPN after filtration. The last column shows the percent decrease in bacteria populations. With all samples decreasing at least 88.69%, this indicates that biochar is working well to remove bacteria.

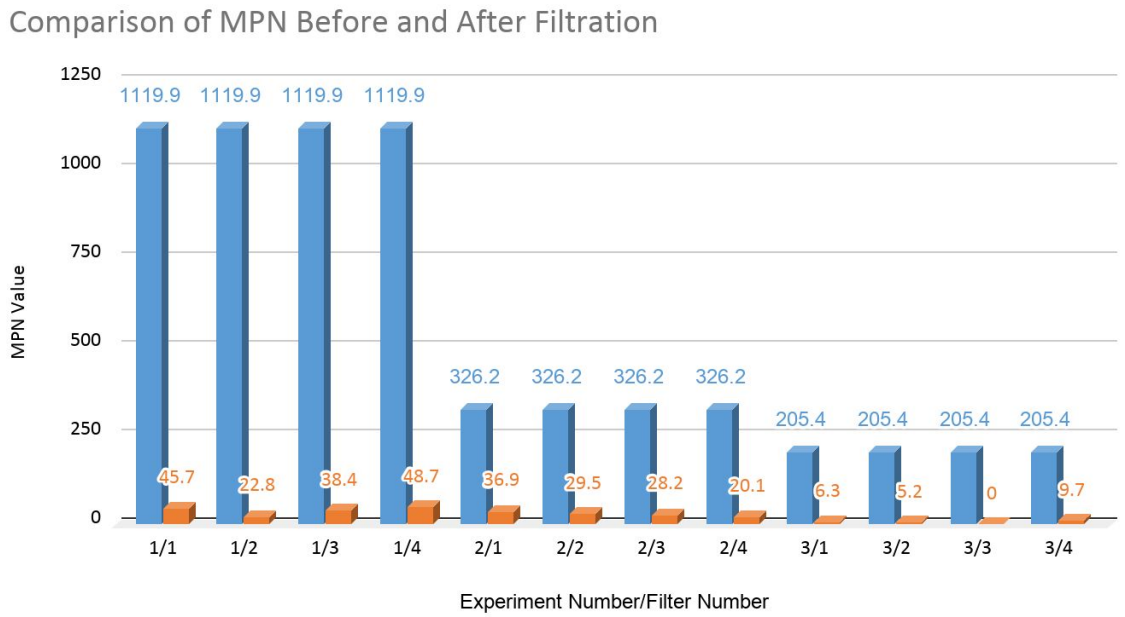

Figure 7. This graph compares side by side the MPN of GR water before and after filtration in all three experiments using all four filters. Blue bars indicate the raw sample of GR water tested alongside the samples that were filtered, orange indicates filtered water run through the filters then incubated and counted.

Discussion

Our research found that filters containing sand, gravel, and biochar were effective at removing *E. coli* from contaminated GR water. We saw decreases of between 88.69% and 100% for the different filter methods and charcoal amounts. These preliminary results demonstrate that a combination of sand and biochar is a viable and sustainable option which, if combined with a container constructed from local materials could be entirely built in Haiti using only Haitian materials. Our brief set of experiments has shown that biochar is something that has huge potential for purifying water of *E. coli* and potentially other pathogens using very simple methods and at a low cost. Based on these preliminary experiments the most important factor that we found to play a role in the efficacy of the removal of contaminants was the amount of charcoal within the filter. Our third experiment showed that the removal of bacteria 100% effectively was done with the filter containing the most biochar. Looking forward, more runs of similar experiments varying the amount of biochar in different filters to solidify this data would need to be done. This project, although preliminary, has established strong starting point in the work to purify water with low cost methods that are both sustainable and renewable. All the materials we used are able to be found or substituted with materials in Haiti, meaning the parts to the filter that we made are readily available, one thing to finish is a simple and effective instruction manual for how to make it.

Future experiments

Future experiments should focus on four variables: 1) biochar size; 2) contact time; 3) sand to biochar ratio; and 4) filter longevity and rejuvenation.

Biochar size

Since surface area may be an important factor in filter effectiveness additional experiments with different sizes of biochar fragments are needed. Controlling the process of crushing the charcoal then separating particles by size through sieving would allow filters to be

made with different biochar sizes which could affect the filtration as more surface area could have more interaction with the water, and thus potentially remove more bacteria. Filters could be constructed using a range of biochar sizes from random uncrushed pieces to dust-sized fragments. Results could then be compared to determine the most effective biochar particle size for filtering.

Contact time with filter

Additional experiments are needed that control flow rate and contact time. One means of changing contact time would be to vary the height of the outlet valve. Previous research has found contact time to be a major factor in biochar bacteria removal[6]. Keeping flow rates controlled and finding the results after 10 minutes to one hour of flow by varying the height of the outlet valve could be done fairly easily. Another way to test this would be ceasing flow and letting water sit in the filter in contact with the biochar for a set amount of time, then letting it drain and comparing various times in terms of bacteria removal.

Sand to Biochar Ratio

Developing an effective biochar amount when compared to sand would be ideal in making something easy to use and implement in Haiti. Finding different ratios and their effectiveness could be a great experiment, keeping the amount of water put through the filter at a constant, one could establish the ideal sand to biochar ratio for that amount of water or filter size (i.e. 2 parts sand: 1 part biochar). This could then be used in Haiti with simple instructions detailing "2 scoops of sand, 1 scoop of biochar." Creating an ideal ratio further eliminates the need for a scale, as aforementioned, something not many households have. By varying the biochar to sand ratio, from more sand to biochar all the way to something like 3 parts biochar: 1 part sand, you could determine how important sand really is to the filtration of water, as the sand weight in our experiments were constant throughout.

[6] Cao, Q., Huang, Z., Liu, S., & Wu, Y. (2019). Potential of Punica granatum biochar to adsorb Cu(II) in soil. *Scientific Reports*, *9*(1), 1–13. https://doi.org/10.1038/s41598-019-46983-2.

Longevity and Rejuvenation

Further experiments to test the longevity of these filters would consist of a long term experiment running a dirty sample through the filter every day and finding at what point in time the filter stops working or decreases in effectiveness. This is an important step in determining the longevity of the filters and setting a time or volume cap so that the filters are not used once “expired” and thus only passing dirty water. This experiment could be continued to determine if there is a means of renewing the filter somehow. Assessing how backflow into the filter effects an expired filter by backflowing it then retesting it with dirty water could be helpful for determining if the filters are renewable. Other areas to research for renewing the filters could be done with boiling water poured through to potentially clear out the nanopores and free the active sites of biochar up again is another variable that could be tested.