**DISINFECTION BY-PRODUCTS OCCURRENCE AND *ESCHERICHIA COLIFORM* REMOVAL IN A POINT-OF-ENTRY CISTERN PURIFICATION UNIT**

by

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# ABSTRACT

This research aims to develop and test a Point-of-Entry Cistern Purification Unit (POE-CPU) to guarantee water quality for household purposes, with an emphasis on turbidity, *E. coli* removal and minimal occurrence of disinfection by-products (DBPs). Many countries, especially underdeveloped countries lacking water treatment plants, depend on rainwater collection for their water supply. There is great potential for this supply to be exposed to contamination at the collection point, due to pollution, animal waste and deposition of particulate matter. Other contamination factors, such as aged cistern structures, poor roofing maintenance, pipe corrosion, etc., can result in infectious diseases and other pathogenic illnesses. DBPs have been a rising concern for regulatory agencies, such as United States Environmental Protection Agency (USEPA) and World Health Organization (WHO), because of their toxicity and probable carcinogenic effects. With these factors in mind, a lab-scale POE-CPU, composed of gravel and sand filters and disinfection unit, was developed and tested. Rainfall was collected periodically, pumped through the system and disinfected with controlled amounts of sodium hypochlorite. Analyses were conducted for physiochemical and biological characteristics such as turbidity, pH and *E. coli*, and the concentration of trihalomethanes as surrogate DBPs in the effluent water. The POE-CPU achieved 44% removal of turbidity and 4-log removal of *E. coli* in disinfection samples but exceeded (barely) USEPA Drinking Water Standards. DBPs results varied greatly because of organic matter concentration in the water, but for the most part complied with the 80 ppb standard. Additional experimental runs were made either with calcium alginate (AG) bead or activated carbon (AC) as innovative addition for the removal of heavy metals. AG treatment excelled over both original and AC treatment by removing and average of 55% turbidity, producing no detectable DBPs and achieving 4-log removal of *E. coli*.

# RESUMEN

Esta investigación tiene como objetivo desarrollar y probar una unidad de punto de entrada de purificación de cisternas (POE-CPU) para garantizar la calidad del agua para uso doméstico, con un énfasis en la turbidez, la eliminación de *E. coli* y la presencia mínima de productos de desinfección (DBPs). Muchos países, especialmente los países subdesarrollados que carecen de plantas de tratamiento de agua, dependen de la recolección de agua de lluvia para su abastecimiento de agua. Hay una alta probabilidad de que este suministro esté expuesto a contaminación en el punto de colección, debido a los residuos de animales y la deposición de partículas. Otros factores de contaminación, como la edad y el mantenimiento de la cisterna, el pobre mantenimiento de los techos, la corrosión de tuberías, entre otros, pueden resultar en enfermedades infecciosas y otras enfermedades patógenas. Los DBPs han sido motivo de creciente preocupación para las agencias reguladoras, tales como la Agencia de Protección Ambiental de Estados Unidos (USEPA) y la Organización Mundial de la Salud (WHO), debido a su toxicidad y posibles efectos cancerígenos. Con estos factores en mente, un POE-CPU a escala de laboratorio, compuesto por filtros de grava y arena y una unidad de desinfección, fue desarrollado y probado. El agua de lluvia se recolecto periódicamente, se bombeo a través del sistema y se desinfecto con cantidades controladas de hipoclorito de sodio. Se realizaron análisis para las características fisicoquímicas y biológicas tales como la turbidez, pH, *E. coli*, y la concentración de cloroformo en el agua efluente del sistema. El POE-CPU logro eliminar un 44% de la turbidez y una eliminación mayor de 4 log de *E. coli* en las muestras de desinfección, pero superaro levemente los estándares de la USEPA para agua potable. Resultados de DBPs variaron grandemente debido a la concentración de materia orgánica, pero para la mayor parte cumplieron con el estándar de 80 ppb. Otras corridas experimentales fueron realizadas con

cuentas de alginato de calcio (AG) o carbón activado (CA) como adición innovadora para la eliminación de metales pesados. El tratamiento de AG se destaco sobre el tratamiento original y el AC eliminando un promedio de 55% de la turbidez, produciendo concentraciones de DBPs no detectables y alcanzando una eliminación mayor de 4-log de *E. coli*.

*To my loving and supporting parents,*

*Milagros & Russell*

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# 1. INTRODUCTION

Throughout the last decades a substantial growth of the world population has caused an enormous increase in the use of our water bodies not only for human consumption but also for industrial uses and manufacture. With this growth come shortages of potable and clean water and an increase in wastewater production. Wastewater typically contains high concentrations of heavy metals, pathogenic and non-pathogenic bacteria as well as many other pollutants and is often discharged into rivers causing contamination. With this in consideration arises the concern as to where we will acquire sufficiently clean water for potable use in our country. Developed countries have already responded to this increase of polluted water bodies and have established water treatment technologies to remediate the situation and be able to provide safe drinking water for the public, but many underdeveloped countries don't fare as well. According to the World Health Organization (WHO, 2011), 88% of the diarrheal deaths, which occur mostly in underdeveloped countries, are due to unsafe water, inappropriate sanitation and lack of hygiene. Because of this health risk factor many countries have turned their attention to rainwater as a cleaner and safer alternative water supply for every day needs.

Rainwater harvesting (RWH) is an old technology that is now being explored as a possible solution for water scarcity. Typical RWH occurs with water barrels connected to the residence or building roof spouts.  The water collected can be and is used for non potable purposes, but with the appropriate treatment it has great potential for potable uses. Rainwater collected from roof spouts is not without its hazards. Rainwater quality can be influenced by many factors including air contamination, weather condition and biological contamination. Air contaminants, such as smog, cause the rainwater to be acidic and when in contact with any organic matter they will cause decomposition and production of other contaminants such as nitrates. Particularly to the

Caribbean, dust clouds from the Sahara desert cause increases in rainwater turbidity. Other weather phenomena, such as heavy rains and winds also affect turbidity. Biological contamination factors are influenced by birds and other animals that have contact with the roof. Most of the biological contamination comes from *Escherichia coliform* bacteria, better known as *E. coli*. This bacteria is a natural stomach flora secreted in the feces of humans and other warm blooded animals, which can be harmful to human health (WHO, 2011). For example, Enterohaemorrhagic *E. coli* (EHEC) is a pathogenic strain that if found in water and/or food can cause abdominal cramps, diarrhea, fever, or vomiting. For immune challenged individuals, such as the elderly and young children, EHEC infection can lead to haemolytic uraemic syndrome (HUS) characterized by acute renal failure, haemolytic anaemia and thrombocytopenia (WHO, 2011). Other contaminants in rainwater can be brought by roofing treatments, including heavy metals. Typical heavy metals found in rainwater are copper, zinc and lead which can cause liver, kidney and pancreas disorders, decreased fetal development and anaemia and brain damage in children (Lye, 2009).

Considering the hazards found in rainwater, there is a need to develop a treatment that will improve water quality to comply with the existing potable water standards. The most common treatment systems include sand filtration and disinfection, typically using a sodium hypochlorite solution. Even though the use of chlorine at the correct dosage can achieve 4-log removal it can also be hazardous because of disinfection by-products (DBP's). DBP's from chlorine disinfection are typically caused by the interaction of chlorine and organic matter. This interaction may produce Trihalomethanes (THM's), haloacetic acids (HAA) and many others that are considerably harmful and/or toxic with short or long term exposure. The United States Environmental Protection Agency (USEPA) has recognized the health risk of DBP's and it is enforcing the Stage 2 DBP rule which strengthens public health protection for customers of systems that deliver disinfected water by requiring such systems to comply with maximum contaminant levels (USEPA, 2009).

Rainwater harvesting and treatment presents a solution for the growing need of a safer, low cost, and more readily available water supply. Because of its significantly lower levels of contamination, rainwater would typically require less treatment which will result in less DBP's concentrations. With sufficient research rainwater could become an essential tool to fight future water scarcity with reduced health and environmental impacts.

## 1.1. Scope and objectives

Many studies and research aim at the creation of a filtration and disinfection system with the best achievable technologies. However, because of the rising concern of the lack of healthy and safe drinking water, there is a need for more investigation. Even though rainwater harvesting has been a technology that has existed for many years, its application as the main drinking water source for households and communities hasn't been explored enough. New research should be focused on developing small filtration systems that are cost effective and relatively easy to use by the general public. Special considerations for the system must include, but not be limited to, removal of emerging pollutants, such as heavy metals and disinfection by-products.

### 1.1.1. Scope

The overall goal of this study is the development of a low-cost, efficient POE-CPU for those countries and communities that rely on rainwater as their main and/or alternative water resource. The system is intended to be connected to rooftop spouts for rainwater treatment which will be later stored and used as needed. To meet this goal, a lab-scale POE-CPU purification unit was tested with rainwater collected at the field.

### 1.1.2. Objectives

To achieve the goal aforementioned, this study specifically aims to:

- Assess the general physical-chemical water quality parameters in the effluent of the POE-CPU unit, and its compliance with the drinking water standards;
- Evaluate the POE-CPU unit for 4-log disinfection of *E. coli* with minimal to no DBPs; and
- Evaluate the adsorption capacities of the alginate bead filter for future innovation of the POE-CPU.

# 2. LITERATURE REVIEW

## 2.1. Rainwater harvesting and treatment

Water scarcity is a major problem in many developing countries. Mwabi et al. (2011) mentions that an estimated 1.1 billion people, most from developing countries and rural communities, do not have access to safe potable water. Depending on precipitation intensity, rainwater presents potential as a direct source of water. In addition, its proper management could reduce water crisis in some of these regions. Rainwater harvesting is a technology where surface runoff is effectively collected during rainfall periods and used for multiple purposes in the household (Helmreich and Horn, 2009). Rainwater reuse offers a number of benefits (Kloss, 2008) such as:

- provides an inexpensive supply of water,
- augments drinking water supplies,
- reduces stormwater runoff and pollution,
- reduces erosion in urban environments,
- provides water that needs little treatment for irrigation or non potable indoor uses, and
- helps reduce peak summer demands.

Harvested rainwater can be used for rainfall fed agriculture or as a water supply for households. Cisterns are typically used for rainwater collection and the feasibility of its use depends on amount of storage needed for household use and adequate roof area (Morris et al., 19984). Rainwater typically has a pH of approximately 5.5 and depending on location and method of collection it might be polluted by bacteria and hazardous chemicals requiring treatment before usage (Lye, 2009). For purification of harvested rainwater, point-of-use or household treatment methods improve quality and reduce risk of illness in the absence of improved sanitary conditions (Mwabi et al., 2011).

### 2.2. *Escherichia coli*

*E. coli* is a natural stomach flora secreted in the feces of humans and other warm blooded animals, which can be harmful to human health. *E. coli* contamination of the water resources can result from municipal wastewater discharges, illegal sewer discharges and farm animal contact. Pathogenic strains of *E. coli*, such as Enterohaemorrhagic *E. coli* (EHEC), can cause abdominal cramps, diarrhea, fever, or vomiting. According to WHO, the EHEC infection can cause HUS[1] particularly in young children and the elderly. Patients with this syndrome can suffer acute renal failure, haemolytic anaemia and thrombocytopenia (WHO, 2011). It is a top priority of treatment systems to achieve 4-log removal of total coliforms and comply with the USEPA Maximum Contaminant Level Goal (MCLG) for drinking water, which states that *E. coli*, total and fecal coliform are not to exceed zero (0) colony forming units (CFU) per 100 mL in order to not cause harm to the public.

### 2.3. Filtering Media

Filtering media can be prepared with a variety of materials but typically consists of beds of different types of sand. Slow sand filtration (SSF) has the capacity to reduce a variety of pathogens and its low cost and simple operation makes it optimum for emerging countries (Bauer et al., 2010). Other applications for sand filtration are with planted and non planted columns (Wand et al., 2007), biosand filters (Mwabi et al., 2011; Elliot et al., 2008), combined with

[1] haemolytic uraemic syndrome

gravel beds and variation in materials for chamber construction. Efficiency of the sand filter will depend on parameters such as turbidity, temperature, filter depth and filtration rate (AWWA, 1999). Granular Activated carbon (GAC) can also be used as filtering media. Although GAC is typically employed for its adsorptive capacity to remove micro pollutants and organic matter, its rates and grain sizes are comparable to rapid sand filtration and it possess higher bio-film concentration (Hijnen et al., 2010). Filtering material aside the primary concern would be that the effluent complies with USEPA regulations and standards (USEPA, 2009). According to USEPA regulations, the filter's effluent should not exceed a turbidity of five (5) NTU at all times and at least 95% of the samples must not exceed one (1) NTU for a time frame of one month. Other USEPA regulations are shown in Table 1.

**Table 1: Extract from USEPA Primary Drinking Water Standards (USEPA, 2009)**

| Contaminant | MCLG (mg/L) | Potential Health Effects from Long-Term Exposure Above the MCL (unless specified as short-term) | Sources of Contaminant in Drinking Water |
|---|---|---|---|
| **Heterotrophic plate count**[1] | n/a | No health effects; it is an analytic method used to measure the variety of bacteria that are common in water. The lower the concentration of bacteria in drinking water, the better maintained the water system is. | HPC measures a range of bacteria that are naturally present in the environment |
| ***E. coli*** | Zero | Not a health threat in itself; it is used to indicate whether other potentially harmful bacteria may be present | Naturally present in the environment; as well as feces; fecal coliforms and *E. coli* only come from human and animal fecal waste. |
| **Turbidity**[2] | n/a | Measure of the cloudiness of water. It is used to indicate water quality and filtration effectiveness. Higher turbidity levels are often associated with higher levels of disease-causing microorganisms such as viruses, parasites and some bacteria. These organisms can cause symptoms such as nausea, cramps, diarrhea, and associated headaches. | Soil runoff |
| **Chlorine (as $Cl_2$)** | MRDLG =4 | Eye/nose irritation; stomach discomfort | Water additive used to control microbes |

Note: [1] HPC: No more than 500 bacterial colonies per milliliter (USEPA, 2009).

[2] Turbidity: For systems that use conventional or direct filtration, at no time can turbidity (cloudiness of water) go higher than 1 nephelolometric turbidity unit NTU), and samples for turbidity must be less than or equal to 0.3 NTU in at least 95 percent of the samples in any month. Systems that use filtration other than the conventional or direct filtration must follow state limits, which must include turbidity at no time exceeding 5 NTU (USEPA, 2009).

### 2.4. Heavy metal adsorption

The increase in industrial activities has created an intense need for heavy metals removal and, according to Gok and Aytas (2005), natural occurring biopolymers are now being used because of their excellent adsorption for multivalent metal ions. Even though rainwater is considered to be cleaner than any other surface water it can be exposed to many heavy metals deposited by roof treatments and pipe corrosion. Table 2 presents some heavy metals present in rainwater (Lye, 2009) and their effects on health (USEPA, 2009). Because of the health risks listed there is an urgent need for remediation technologies. Alginate gel is a new material characterized by its adsorption capabilities of heavy metal ions like cadmium, copper, zinc, lead and chromium (Lin, 2005).

**Table 2: Heavy metals in rainwater and their effect on human health (Lye, 2009; USEPA, 2009)**

| Heavy Metal | Harm | Other effects |
|---|---|---|
| **Cooper** | Short term exposure: Gastrointestinal distress<br>Long term exposure: Liver or kidney damage | Corrosion of household plumbing systems; erosion of natural deposits |
| **Lead** | Infants and children: Delays in physical or mental development; children could show slight deficits in attention span and learning abilities<br>Adults: Kidney problems; high blood pressure | Corrosion of household plumbing systems; erosion of natural deposits |
| **Zinc** | May cause cosmetic effects | None listed |

### 2.5. Disinfection by-products (DBPs)

The amount of organic matter concentration in raw water has become an issue of high concern because of the possibilities of DBPs occurrence when submitted to treatment. By-products of humic acid and conventional water treatment processes can be Trihalomethanes (THM) and Haloacetic acids (HAA), which are known as carcinogenic and hazardous to health (Lowe, 2008). Table 3 shows a summary of two (2) common disinfection processes and their by-products. Care must be taken when choosing the disinfection method so as to not aggravate the emergence of by-products. Quoting Ashbolt (2004), many agencies are using chloramines disinfectant to avoid chlorine disinfectant by-products, and in the process possibly creating one more harmful.

**Table 3: Disinfection and their by-products (Ashbolt, 2004)**

| Disinfectant | Reactions | By-Product | Harm |
|---|---|---|---|
| **Chlorine** | Natural organic matter (humic acids and fulvic acids) | Trihalomethanes (THMs) and haloacetic acids | Carcinogen |
| **Chloramine** | Chlorine plus ammonium yielding monochloramine | Nitrosodimethylamine (NDMA) | Carcinogen |

Since 1998, the USEPA has established the Stage 1: Disinfectant/Disinfection by-products rule, in which it states new regulations for Total trihalomethanes (TTHM) to 80 ppb, Haloacetic acids (HAA5) to 60 ppb, Bromate to 10 ppb and  Chlorite to 1.0 ppm. Table 4 presents the carcinogenic risk assessment for DBP at Aqua III advanced wastewater treatment works.

**Table 4: Cancer risk assessment for DBPs at Aqua III**

| **Chemical** | **Concentration ($\mu g l^{-1}$)** | **Cancer Risk[1]** | | |
|---|---|---|---|---|
| | | $50^{th}$ percentile | Mean | $95^{th}$ percentile |
| **Bromodichloromethane** | 0.48 | $1.3x10^{-7}$ | $4.9x10^{-7}$ | $1.8x10^{-6}$ |
| **Chloroform** | 0.51 | $6.1x10^{-9}$ | $2.2x10^{-8}$ | $8.9x10^{-8}$ |
| **Chloromethane** | 0.11 | $1.6x10^{-9}$ | $6.1x10^{-9}$ | $2.5x10^{-8}$ |

Notes: [1] Assumed 2 L per day consumption of water

Similarly, USEPA has already established Maximum Contaminant Levels (MCL) for DBP’s which are presented in Table 5. As of 2006, USEPA has developed Stage 2 DBP rule (USEPA, 2005) which is intended to reduce potential cancer and reproductive and developmental health risks from DBP's by enforcing the requirement to meet maximum contaminant levels for trihalomethanes and some haloacetic acids.

**Table 5: DBPs regulation (USEPA, 2005)**

| DBP | Treatment Measures |
|---|---|
| Total Trihalomethanes ( TTHM) | 80 ppb |
| Haloacetic Acid | 60 ppb |
| Bromate | 10 ppb |
| Chlorite | 1 ppm |

# 3. MATERIALS AND METHODOLOGIES

## 3.1. Materials

### 3.1.1. Rainwater harvesting

Rainwater was collected from rooftop spouts. To cover dissimilar characteristics of rainwater, rainwater was collected in both residential and commercial zones. Rainwater was collected and stored in Nalgene 5 gallon bottles for no more than 24 hours to preserve biological characteristics of rainwater.

### 3.1.2. Escherichia coli

Non pathogenic *E. coli* strain ATCC 15597 was used and its medium was obtained from Cole Parmer. They were prepared for experimental use through enrichment-culture technique. Other materials used for cultivation include Erlenmeyer flasks (250 mL and 500 mL), pipette (1 mL), graduated cylinder (100 mL) and caps. Experiments for *E. coli* inoculation required one (1) liter Erlenmeyer flasks, Clorox, pipette (1 mL), Millipore filtering unit, membranes and Petri dishes.

### 3.1.3. Filtering media

The system consisted of two (2) filters. The first filter had 8.49 kg of commercial gravel medium ranging in sizes of 0.635~1.905 cm. The second filter consisted of a sand medium with three (3) beds of varying particle size. Table 6 presents the sand distribution. The filter medium was contained in a cylindrical crystal column with a diameter of 8 inches and 24 inches high.

**Table 6: Sand distribution in secondary filter**

| Media | Size | Total Weight (kg) | Weight (%) |
|---|---|---|---|
| **Course Sand** | Global No. Sieve Size 30/65<br>Effective size = 0.18 mm | 1.87 | 25 |
| **Medium Sand** | Global No. Sieve Size 20/30<br>Effective size = 0.55 mm | 3.75 | 50 |
| **Fine Sand** | Global No. Sieve Size 6/20<br>Effective size = 1.10 mm | 1.87 | 25 |

### 3.1.4. Adsorption with calcium alginate beads

The alginate beads were prepared with 2% sodium alginate solution dropped in a 0.5 M calcium chloride solution. Other equipment used for this process includes 50 mL plastic syringe, syringe pump and beakers. The preparation of the sodium alginate solution consists of adding 10 grams to Di-ionized (DI) water to achieve a solution of 500 mL (Gok and Aytas, 2009; Papageorgiou et al., 2006). The calcium chloride solution was prepared by adding 55.5 gms of calcium chloride to DI-water to make a 1 L solution. Using a syringe and a mechanic syringe pump, the alginate solution was pumped drop-wise into the calcium chloride solution. The pump was set at a rate of 0.5 mL per minute. Based on the reviewed literature 200 mL of alginate solution was dropped in 1 L of calcium chloride solution, so two (2) calcium chloride solutions were prepared to comply with an approximate of 400 mL of alginate solution. During the process the solutions were constantly mixed with a magnetic stirrer. The beads were stored for 24 hours in a calcium chloride solution, after which they were washed with and let stand in DI-water. The beads were dried at room temperature in the hood. Figure 1 shows a picture of the preparation.

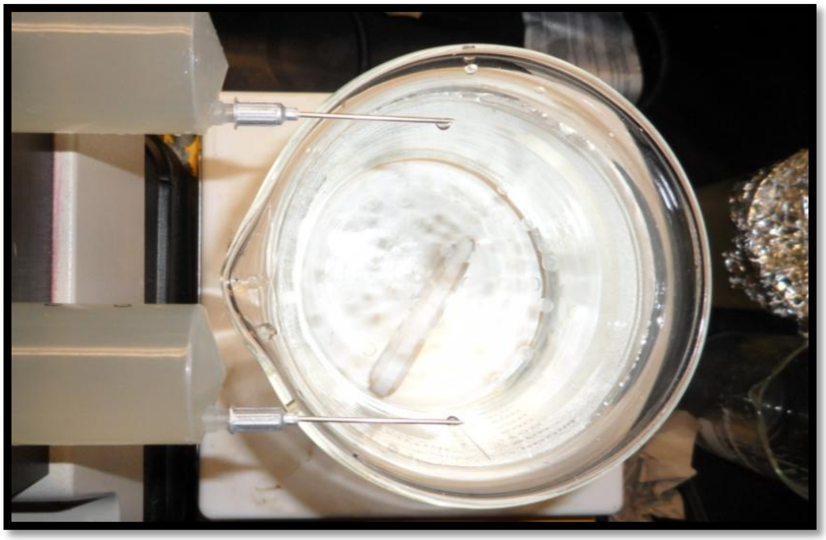


**Figure 1: Bead preparation**

### 3.2. Methods

#### 3.2.1. *E. coli* reactors and inoculation

The medium for *E. coli* reactors was prepared with 37 grams of EC-Medium to 1 liter of DI-water. This medium was sterilized in the autoclave. A volume of 100 mL of the prepared solution was added to Erlenmeyer flask that received 1 mL of *E. coli* stock ampoule. Four (4) enrichment-culture flasks were put on a shaker. After a week of enrichment, 1 mL of grown *E. coli* culture was transferred to fresh growth medium. Figure 2 shows a scheme of the preparations while Figure 3 shows a real time photo of the reactors in the shaker.

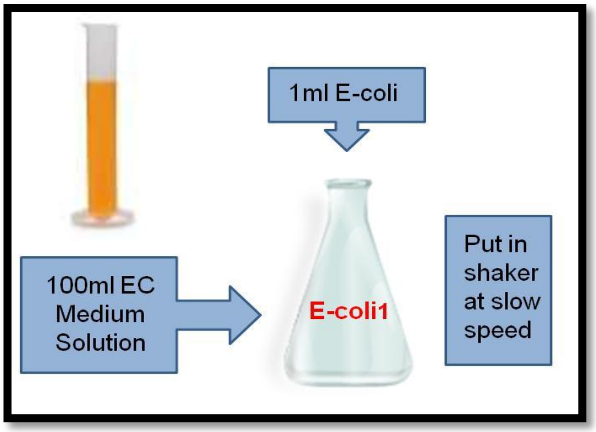



**Figure 2: *E. coli* cultivation reactor preparation**

**Figure 3: *E. coli* reactors in shaker**

An *E. coli* inoculation experiment was prepared in order to determine chlorine dosages for disinfection in *E. coli* spiked rainwater. The experiment consisted of four (4) previously sterilized reactors (Erlenmeyer flasks) of at least one (1) liter with varying spikes of stock solution. A 1% (v/v) stock solution was prepared with 5.25% $NaHOCl_2$ (Clorox) and DI. Figure 4 shows a schematic of the preparation and varying conditions of each reactor.

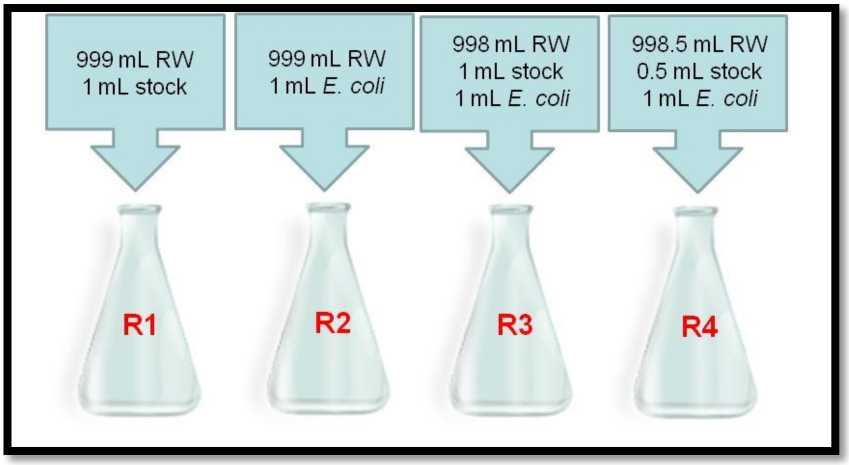



**Figure 4: Four reactor experiment setup[2]**

### 3.2.2. DBP's interaction with *E. coli* and humic acid

To observe chlorine disinfection by-products and its interaction with *E. coli*, a five (5) reactor experiment was developed. Each reactor contained 100 mL sample water and varying amounts of chlorine concentration spike. In some experiments, the sample water was rainwater and in others the sample water was prepared by adding *E. coli* culture to 1 L of rainwater. The stock solution consisted of 1% sodium hypochlorite solution. Figure 5 shows a scheme of the described process, including the chlorine spike for each reactor. A total contact time of thirty (30) minutes was allowed and samples were collected to determine residual chlorine concentration, *E. coli* bacteria concentration and THMs concentration.

Additionally, batch reactor experiments with 2.5% humic acid spike were developed as shown in Figure 6. Hydrogen ion concentrations (pH) was measured in three (3) stages, the first when there was only the solution with humic acid, the second right after spiking chlorine and the

[2] RW- rain water

third after the allotted time. Samples were later analyzed for their chemical oxygen demand (COD), residual chlorine and THMs concentrations.

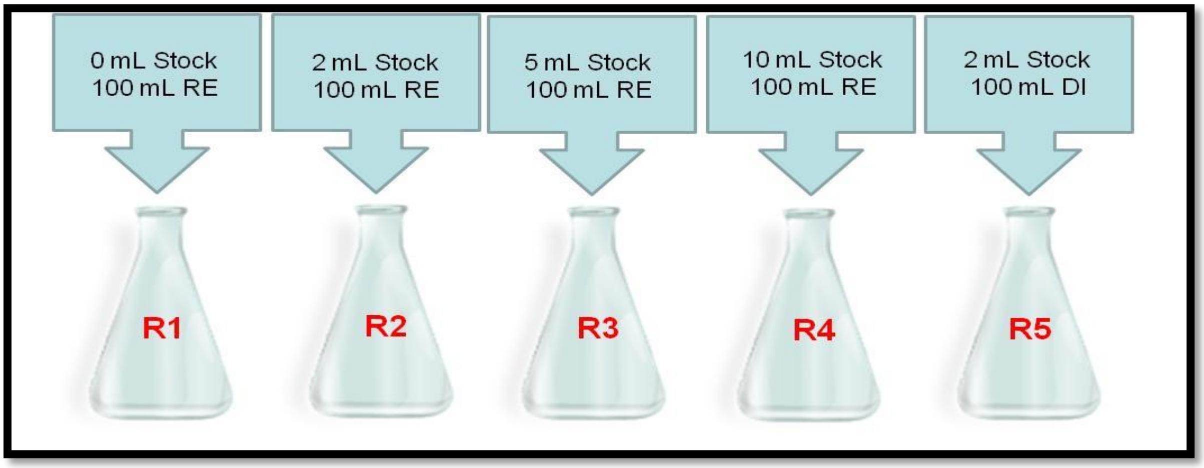



**Figure 5: Reactor for DBPs and *E. coli* interaction**[3]

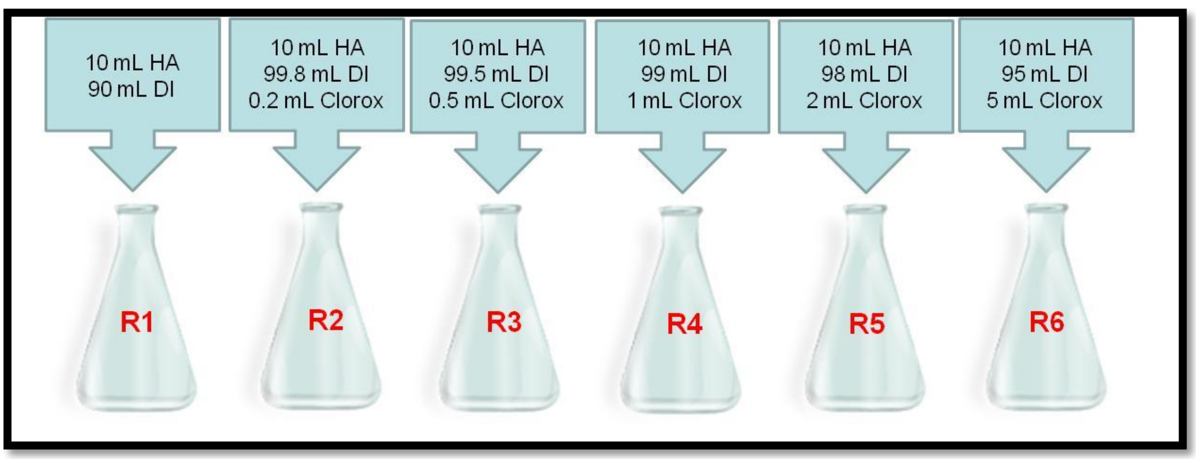



**Figure 6: DBPs interaction with humic acid setup**[4]

[3] RE - sample water; DI- Di-ionized water
[4] HA-humic acid; DI-di-ionized water

### 3.2.3. Adsorption with calcium alginate beads

As collected rainwater often contains heavy metals (Lye, 2009), like copper, lead and zinc, an effort was made to innovate the POE with an addition of calcium alginate (AG) beads. For this, heavy metal adsorption study was conducted in a batch reaction mode. A batch sorption kinetic experiment was done to determine the amount of time necessary for sorption equilibrium between heavy metals and AG bead. Each sample vial contained 0.05 grams of AG beads and 30 mL of 5 ppm lead solution. A total of five (5) vials along with duplicates were prepared and set to spin in a lab shaker. One (1) vial (and its duplicate) was removed after 15, 30, 60, 90 and 120 minutes of contact time, respectively. The beads were removed from the sample and placed in a separate vial to avoid more adsorption. All vials (sample and beads) were stored in the refrigerator until analyzed. Figure 7 shows a schematic of the vial preparation.

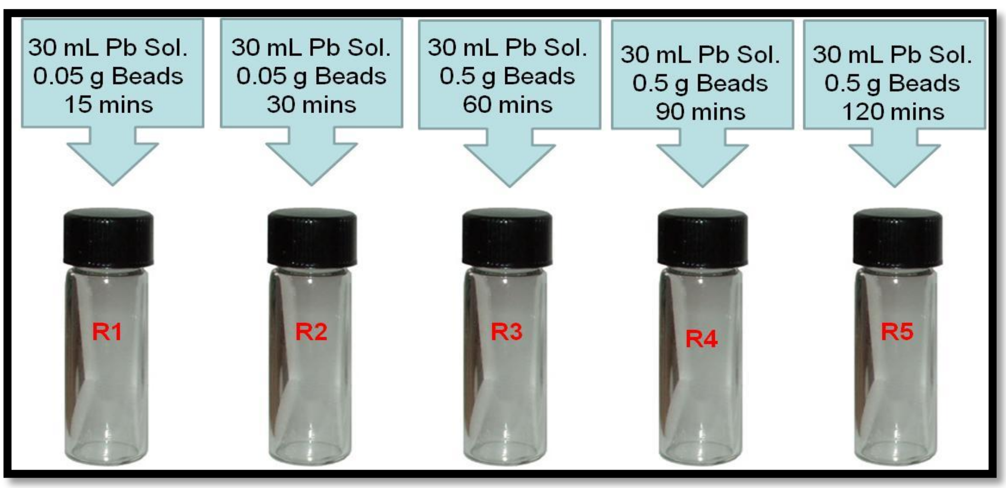



**Figure 7: Batch reactor procedure for kinetics experiment**[5]

The sorption isotherm experiment was conducted with the time acquired from the sorption kinetic study aforementioned. Similar to the kinetics experiment, 30 mL of lead solution

[5] Pb- lead

was added to each vial but the amount of AG bead varied from 0.03 grams to 0.48 grams. The reactors (vials) will be placed in a shaker for the selected optimum contact time determined from the kinetics experiments. Figure 8 shows the setup for this experiment.

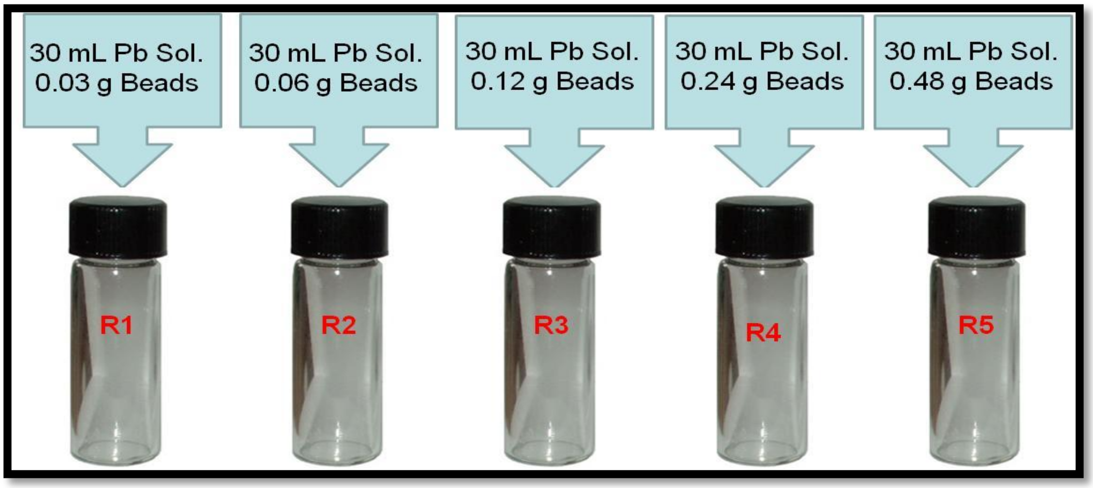



**Figure 8: Lead sorption experiment setup**

An *E. coli* sorption experiment was prepared by adding1 mL of *E. coli* bacteria to 29 mL of working solution which was later added to a 40 mL sample vial. A total of two (2) vials were prepared, one with 0.24 grams of AG beads and the other with 0.24 grams of activated carbon (AC). A schematic of this setup can be seen in Figure 9. The vials were later set to spin for a total time of 30 minutes.

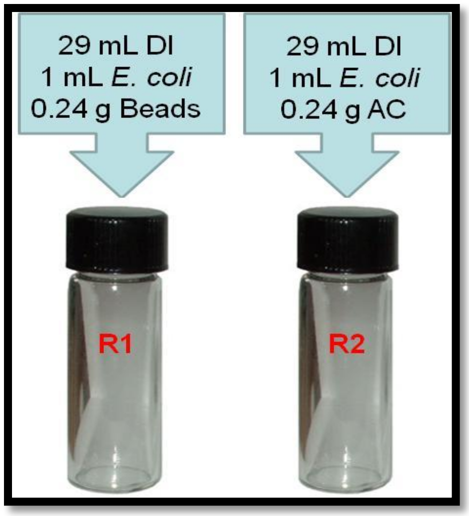



**Figure 9: *E. coli* adsorption experiment setup**

For the purpose of testing AG beads filtering capabilities, two (2) small columns of about 0.69 inch diameter and 3.13 inch length were prepared with 8.7 grams of AG and 6.4 grams of AC, respectively. Rainwater collected was pumped through the columns and kept being pumped until a total of 200 mL of effluent was achieved (approximately 2 hours). Physical-chemical parameters, such as turbidity, pH, temperature and conductivity were measured. The specifications for column setup are shown in Table 7 and a real time photo is shown in Figure 10.

**Table 7: Specifications for filter column setup**

| Parameter | Amount | Units |
|---|---|---|
| AG | 8.7 | grams |
| AC | 6.4 | grams |
| Diameter | 0.6875 | in |
| Length | 3.125 | in |
| Flowrate | 100 | mL/hr |

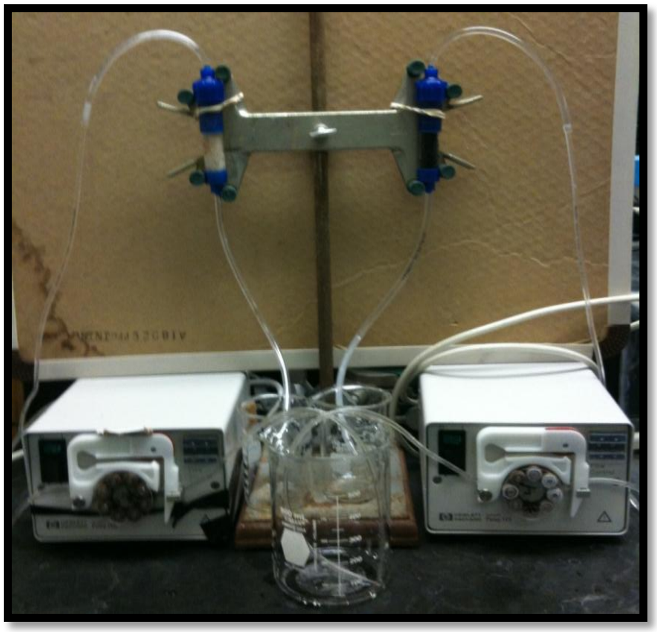


**Figure 10: Filter column setup**

### 3.2.4. Point of entry cistern purification unit (POE-CPU)

The POE-CPU is a simple filtering unit comprised of three (3) unit processes (rainwater reservoir, disinfection tank and backwash water storage), two (2) filters (gravel and sand media) and four (4) pumps (rainwater supply, chlorine supply and back wash pumps). Figure 11 shows a schematic of the design for the POE-CPU. Rainwater was pumped through the system at 3-5 gallons per hour (GPH) and backwash was done when either poor water quality parameters are found or head loss is observed. The system was set to run for an hour without interruptions. If POE-CPU runs were designed for more than an hour an average time of 30 minutes was allowed for the pump to cool off. Sampling was done at the end of each 30 minute run session. Samples were taken from each port and labeled accordingly (Figure 12).

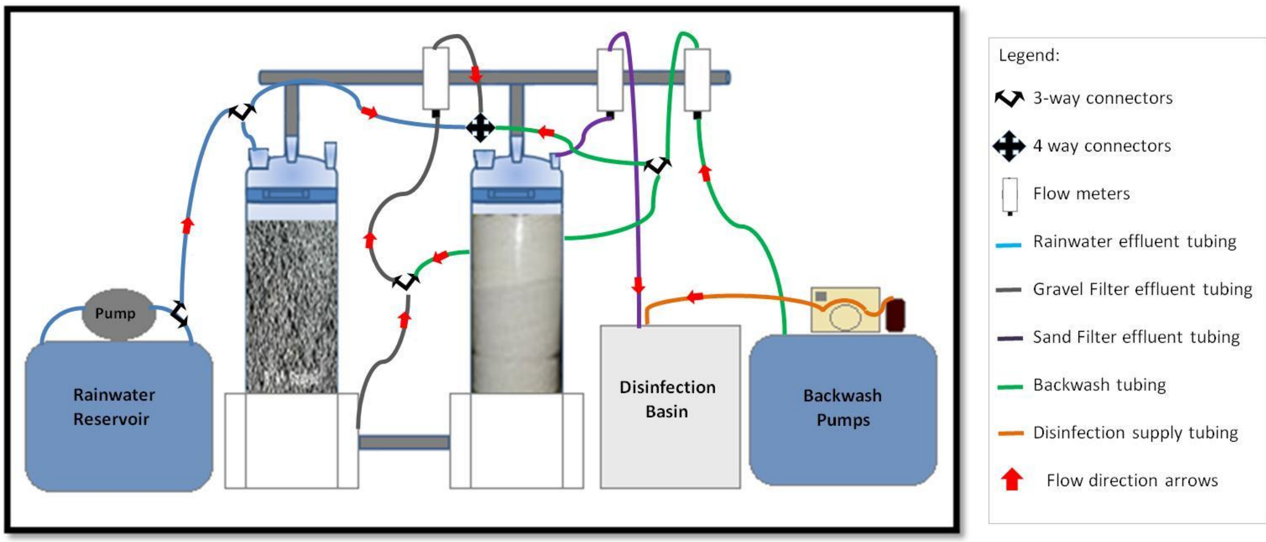



**Figure 11: Schematic of POE-CPU design**

For disinfection purpose, a sample allocation of 100 mL was taken from the sand filter and spiked with a determined amount of chlorine to then allowed 30 minute contact time. Figure 13 shows a real time picture of the POE-CPU system in the current study.

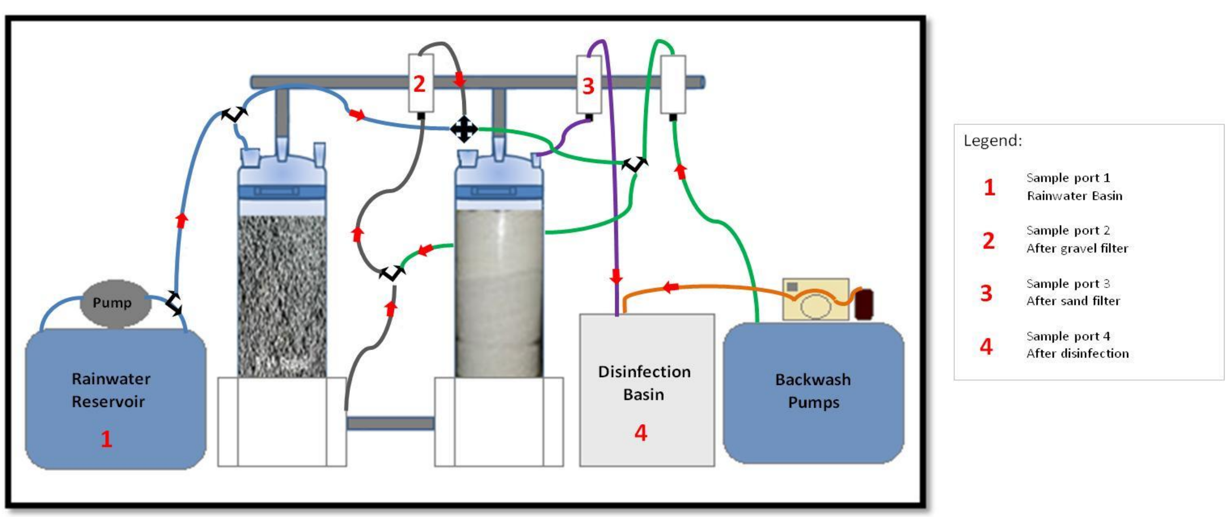



**Figure 12: Sampling ports in the POE-CPU**

**Figure 13: POE-CPU photo**

### 3.3. Analytical method

Water samples taken from each port in the POE-CPU were analyzed in order to determine physical-chemical parameters, contaminant and microbial content. Table 8 summarizes all the analysis for the samples and includes the method and equipment used for each. Note that DBPs analysis was done only for disinfected effluent.

**Table 8: Summary of parameter analysis**

| Parameters | Equipment | Method | Details |
|---|---|---|---|
| **Sampling** | WHIRL-PAK THIO-BAG | - | Sample storage with chlorine neutralization |
| **Chlorine Concentration** | HACH Pocket Colorimeter II, Chlorine | - | HACH, DPD Free Chlorine Reagent |
| **Lead** | Perkin Elmer AAnalyst 400 | Pb | |
| **Fecal Coliforms** | Membrane Filtration Unit | Membrane filtration technique | 0.45 µm opening membrane |
| **pH and temperature** | pH Meter 300 series | - | - |
| **Turbidity** | HACH 2100P Turbidimeter | - | - |
| **Conductivity** | OAKTON CON 6 Acorn Series Conductivity/C Meter | - | - |
| **COD** | HACH Spectrophotometer/ Ultra Low Range COD vials | Reactor Digestion Method, Method 8000 | Ultra low range (0-40 mg/L) and Low range (0 to 150 mg/L) vials |
| **Disinfection by-products** | HACH Spectrophotometer | THM Plus™ Method, Method 10132 | - |

# 4. RESULTS AND DISCUSSION

## 4.1. *E. coli*

### 4.1.1. Life patterns

Bacteriological analysis was done within 24 hrs of sampling or sample preparation. The prepared sample was diluted and filtered through the unit and the membrane was placed in a Petri-dish containing m-FC 2 mL broth ampoules or *E. coli* medium. The incubation time for *E. coli* was twenty-four (24) hours. The results of the daily monitoring of the *E. coli* in the batch reactor are shown in Figure 14.

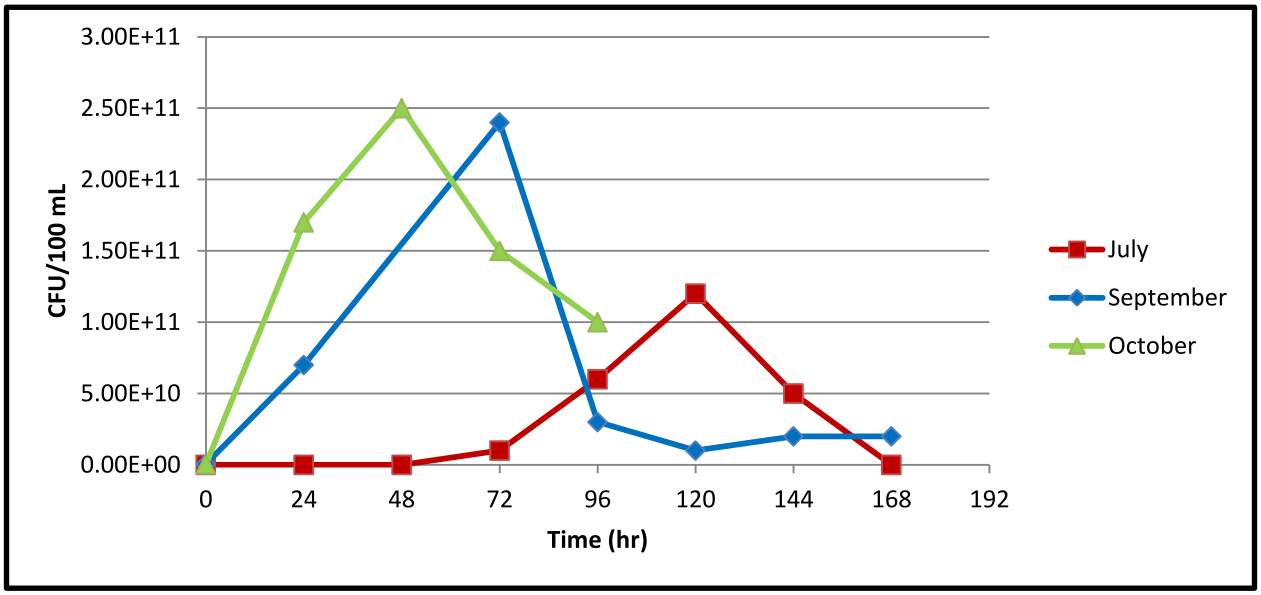



**Figure 14: *E. coli* life patterns ($10^{10}$ dilution)**

The seven (7) day trial was determined during the monitoring made in the month of July, because as can be appreciated, the bacteria growth and death phase are easily distinguished. It can be observed that there was a considerable difference between the bacteria concentration in July and September's experiments. This lag phase shows the time it took the bacteria to acclimate to the new medium. Meanwhile, the September monitoring started with a reactor sampling just before the medium was replenished. The bacteria in this reactor had more time in the medium resulting in a higher concentration. Also note that the monitoring of October was stopped at Day 5 (96 hours) this was because of difficulties with the autoclave, which is essential in the sterilization of the instrumentation due to *E. coli* sample sensitivity. The following figures show growth/death patterns for the same samples. Linear regression where chosen for the figures presented in order to approximate growth/death rates of the *E. coli* in the reactors. Figure 15 shows the average growth rate of *E. coli* at 3.3 x$10^9$ CFU/day, while Figure 16 shows and average of 3.7 x$10^9$ CFU/day.

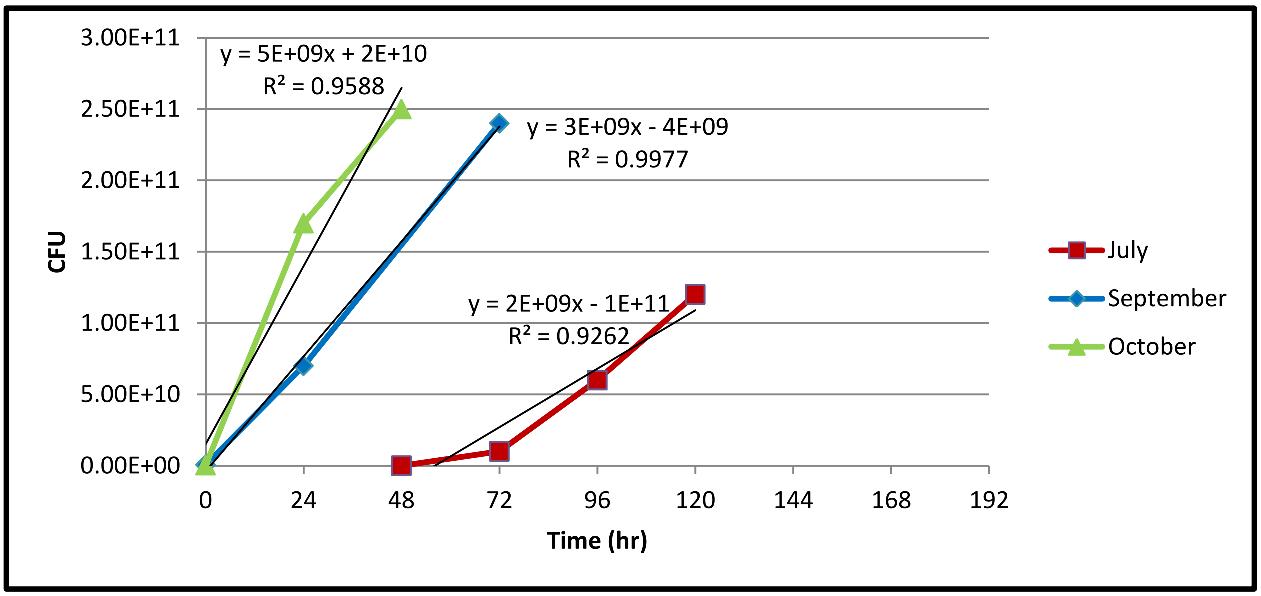



**Figure 15: Growth pattern for *E. coli* culture ($10^{10}$ dilution)**

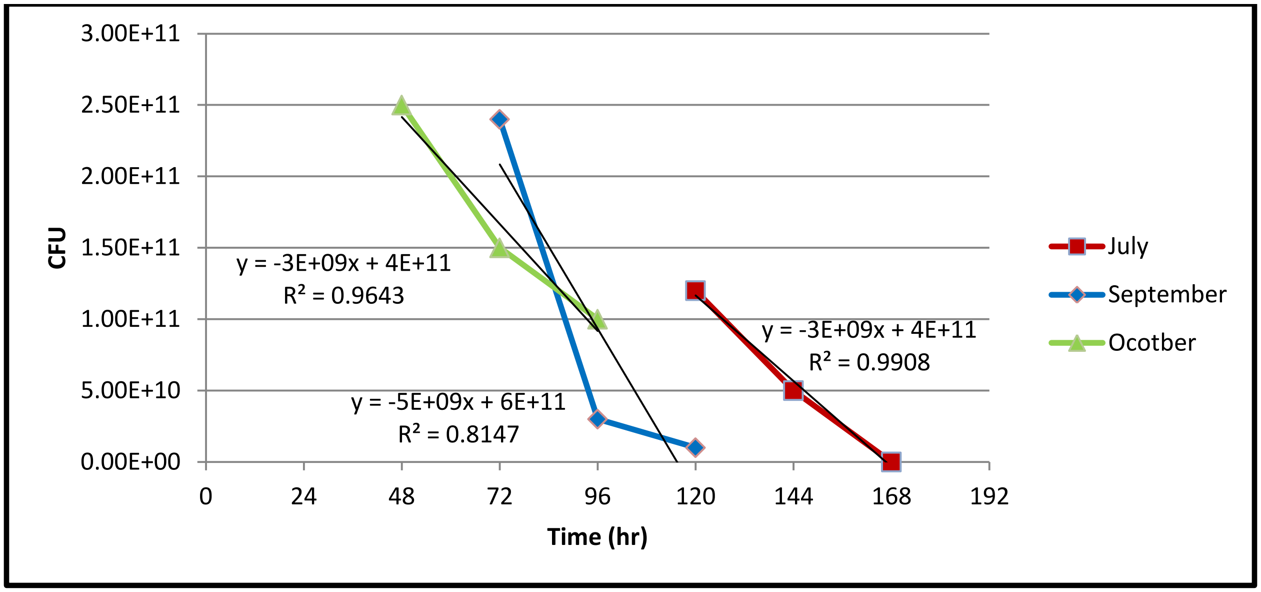



**Figure 16: Death pattern for *E. coli* cultures**

Table 9 shows the average results from all monitoring weeks. These results prove that the 7 day replenishment schedule was appropriate, since there was a great possibility that at the 8th day no significant *E. coli* was present in the reactors. By following these instructions it will guarantee very healthy and highly concentrated bacteria cultivation.

**Table 9: Life rates for *E. coli* cultures**

| Parameter | Growth phase | Death phase | Units |
|---|---|---|---|
| **Rate** | $3.3 \times 10^{9}$ | $3.7 \times 10^{9}$ | CFU/100 mL * hr |
| **Days in effect** | 3.67 (88.08) | 3 (72) | Days (hours) |
| **Total bacteria** | $2.9 \times 10^{11}$ | $2.7 \times 10^{11}$ | CFU/100 mL |
| **Bacteria left in reactor** | | $2.4 \times 10^{10}$ | CFU/100 mL |

### 4.1.2. *E. coli* inoculation

A total of four (4) experiments were done to determine correct disinfectant dosages for *E. coli* inoculation. Figure 17 shows the averaged result for total testing runs (4).

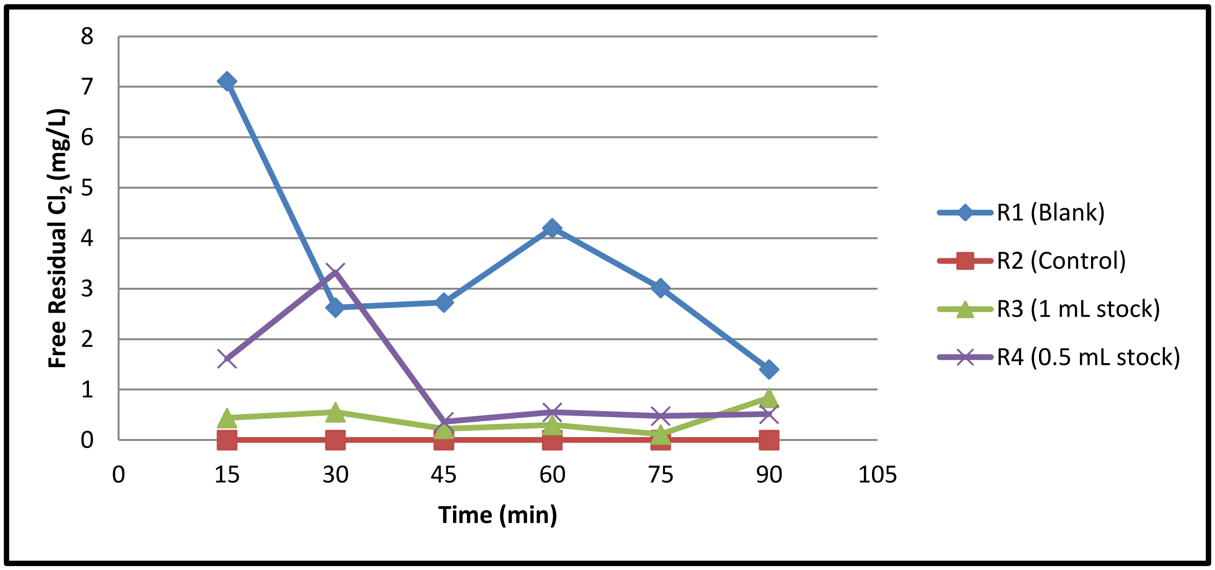



**Figure 17: Free residual chlorine concentration**

Chlorine solution is reacting quickly with bacteria present in the sample as can be seen for both reactors that have *E. coli* and disinfectant (R3 and R4) versus the control reactor (R1) which has no *E. coli*. Comparing reactors R4 and R5 shows that a chlorine spike of 0.5 mL of 1% NaHOCl achieves similar free chlorine concentrations as a 1mL spike, meaning that less chlorine will be available to react with organic matter and create disinfection by-products. As for bacteria concentrations, Figure 18 shows the averaged results from all four (4) experiments. As can be seen both chlorine stock spike achieved 0 CFU after 30 minutes of contact time.

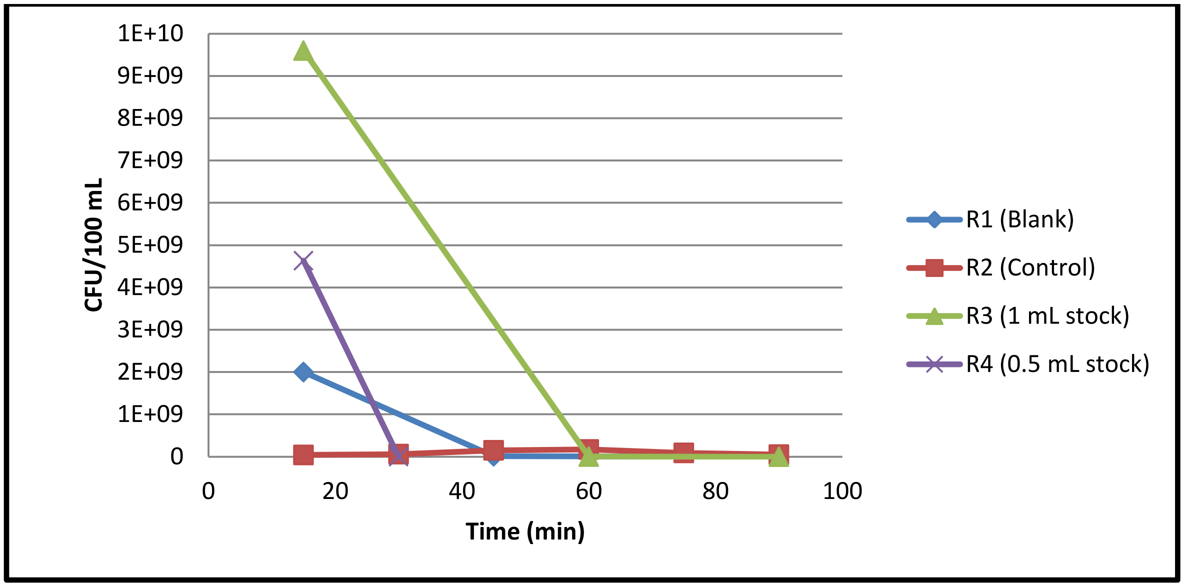



**Figure 18: CFU variation for *E. coli* inoculation experiments**

### 4.2. Disinfection by-products

A total of two (2) experiments were done and their average results are shown in Figure 19. Observations show that an increase in chlorine demand for bacteria inoculation causes a decrease in chloroform formation. This could be to do either low organic concentration in the samples and/or increasing pH.

The following formula shows sodium hypochlorite and water interaction:

$$HOCl + H_2O \leftrightarrow H^+ + OCl^-$$

When calculating reaction rate, increasing pH causes and increase in $OCl^-$ concentrations and a decrease in HOCl. For disinfection purposes HOCl is desirable because of its strength.

$$k_a = \frac{[H^+][OCl^-]}{[HOCl]} = 2.5 \times 10^{-8}$$

That is, if pH was increased with increasing chlorine stock spike, then it would explain the increasing chlorine demand but decreasing chloroforms formation. Considering residual free chlorine in the samples, there is need to present the plotted results from one of the experiments, where there can be clearly seen the trend expected. As can be seen on Figure 19, the residual chlorine and chloroform concentrations remain constant after chlorine demand passes 2500 mg/L (spike of 5 mL stock solution). So based on both figures an assumption can be made that between the ranges of  1000 mg/L and 2500 mg/L chlorine demand there is a pH between 7 and 8, which is causing formation of HOCl and causing increases in residual chlorine.

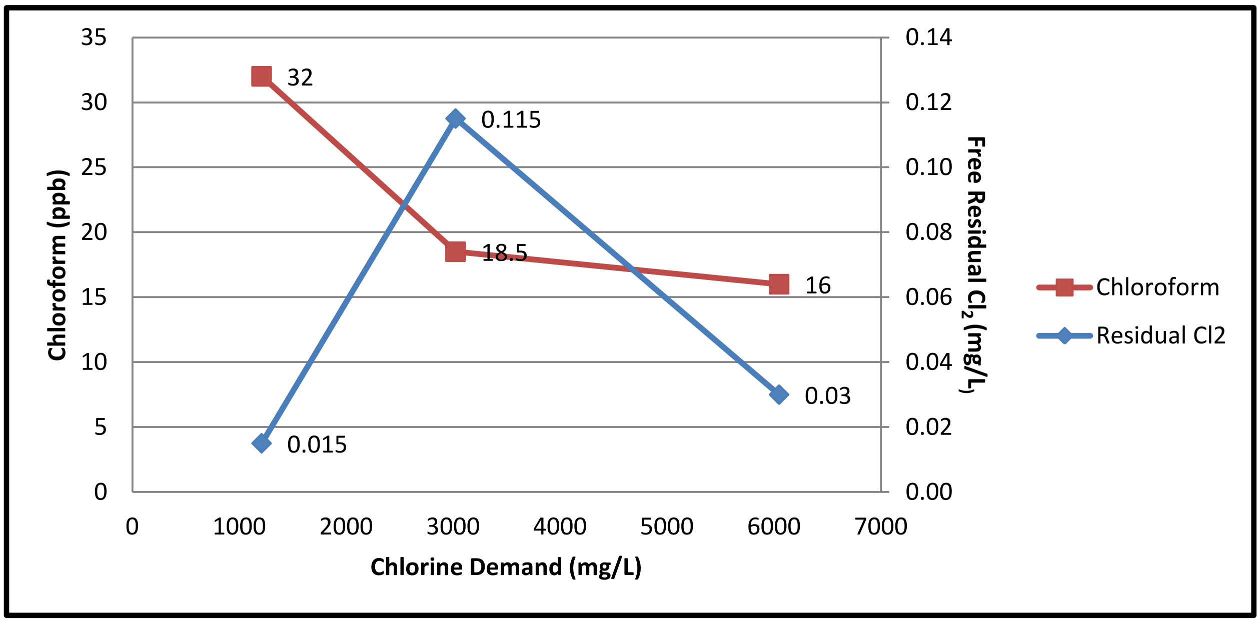



**Figure 19: Chloroform and residual chlorine variations in DBPs experiments**

Now going back to Figure 19, and assuming data point 3 (6000,0.03) for chlorine demand as an outlier, 2250 mg/L (approx. 4.5 mL spike) demand achieves  global minimums for free chlorine and chloroform concentrations  of 0.09 mg/L and  22.5 ppb respectively.

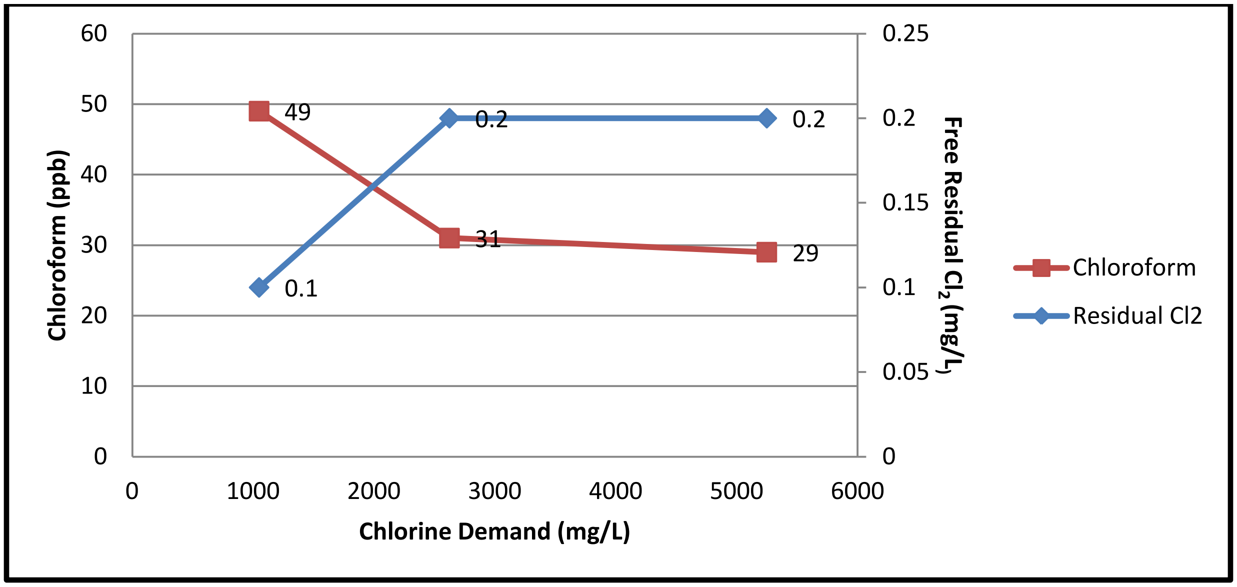



**Figure 20: DBP and residual chlorine in experiment 2**

In order to observe DBPs interaction with humic acid, two (2) experiments where developed and their average results are shown in Figures 21 and 22. These results differ from the experiments above by showing a direct relationship between residual chlorine concentrations and chloroform occurrence. Note that the chlorine demand is half of what it was in the first experiment because there are no bacteria present. Similar to the first experiment, chloroform concentrations started to decrease while chlorine demand increased (Figure 20). Also, in Figure 22, the trend shows that increasing stock spike increases pH, which validates the assumption made on the first experiment. An important observation for all experiments made is that only one (1) sample exceeded USEPA standard of 80 ppb for drinking water, the rest of the samples were well below the limit.

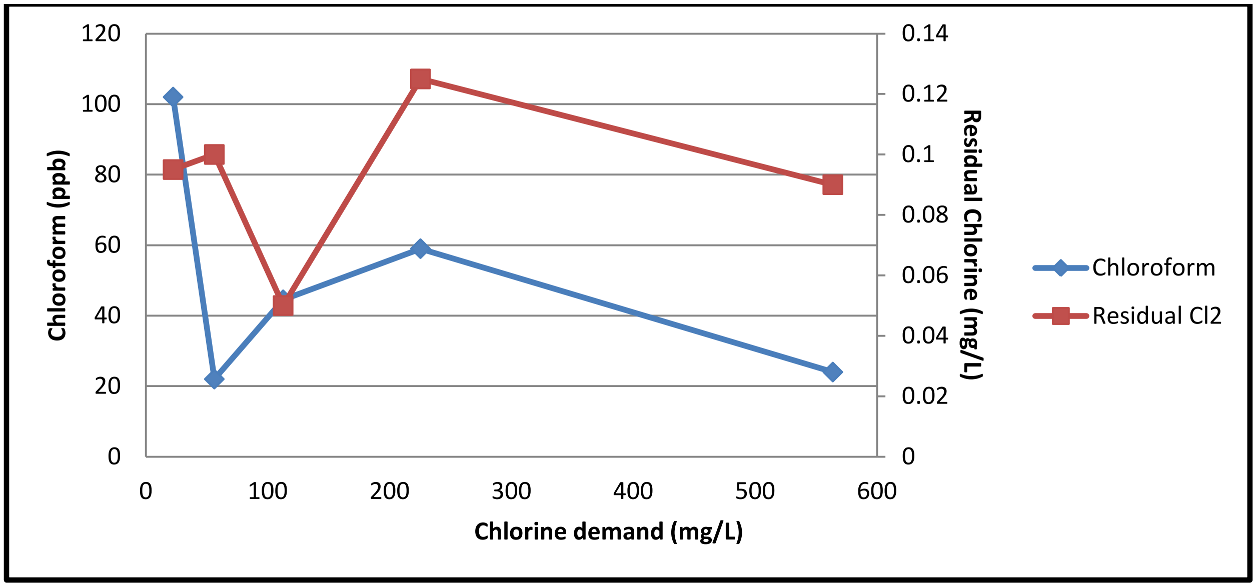



**Figure 21: Chloroform and residual chlorine plots for humic acid DBPs experiments**

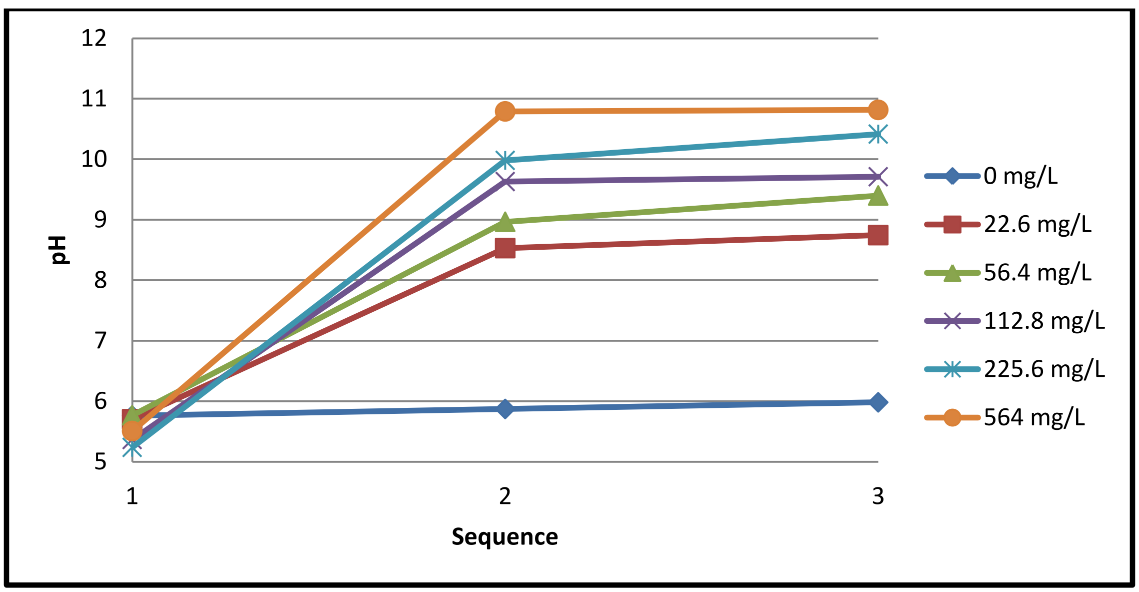



**Figure 22: pH variation in humic acid DBPs experiments**

### 4.3. Calcium alginate beads

The AG beads were prepared as mentioned in the methodology and Table 10 shows their characterization.

**Table 10: Characterization of AG beads**

| Parameter | Dry | Wet | Reduction |
|---|---|---|---|
| **Mass (mg/Bead )** | 0.962 | 12.7 | 92.4% |
| **Volume (µl/Bead )** | 0.638 | 19.6 | 96.7% |
| **Density (g/ml )** | 1.51 | 0.65 | |

Both mass and volume reduction were very high but similar to results found in the literature (Gok and Aytas, 2009). A picture of the beads before drying and after drying is shown in Figure 23.

**Figure 23: AG beads before drying (left) and after drying (right)**

A total of two (2) kinetic experiments were done to determine optimum interaction time between 5 ppm lead solution and the AG beads (Figure 24). In both plots there was a constant trend towards the end of the experiment or 120 minutes. A 50% reduction of the lead in the solution was achieved at 75 minutes where there was an adsorption of 2.5 mg of lead per gram of bead while a 72% reduction was achieved at 120 minutes differing from Gok and Aytas (2009) where it achieved 80% reduction at 90 minutes.

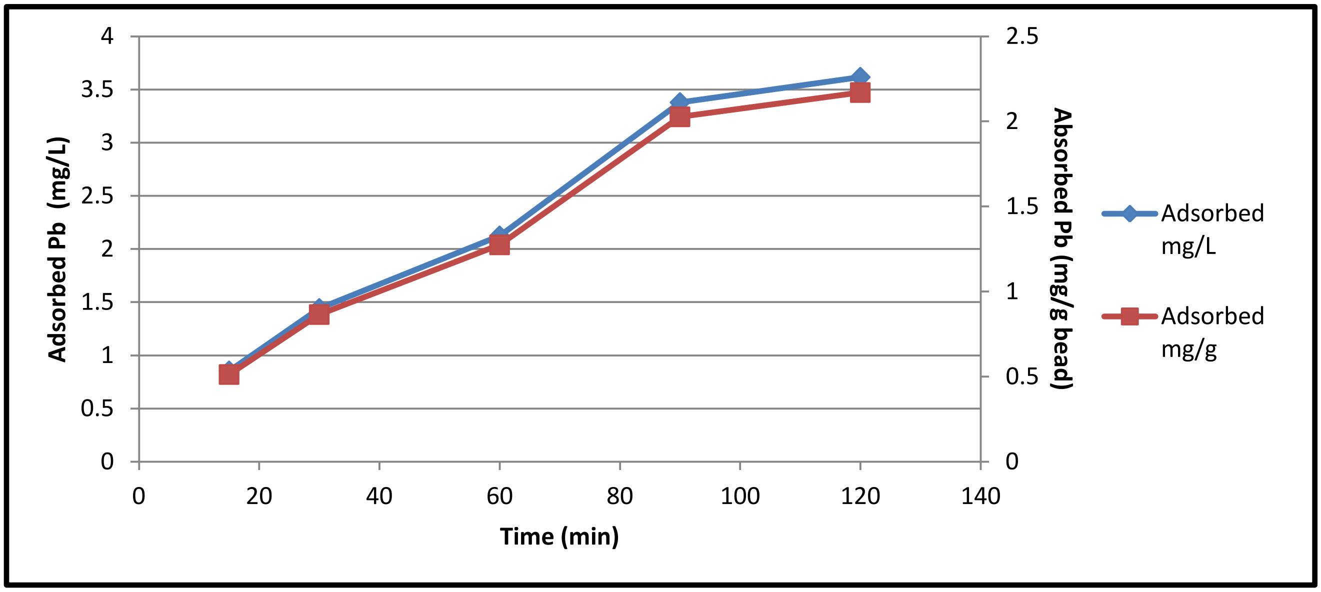



**Figure 24: AG kinetic adsorption results**

Following the results from the kinetics experiment, the sorption experiment was prepared. A total of 120 minutes contact time was allowed and the results for both adsorbed lead in mg/L and adsorbed lead in mg/g of bead are shown in Figure 25. The results showed that lead sorption to AG beads varied from ~90% reduction per 0.06 to 0.48 g AG beads. Another test developed was to determine sorption-desorption properties of the beads. In order to be able to compare the beads properties, the test was also done for activated carbon. Every 30 minutes the beads were transferred to a fresh 5 ppm lead sample for 2.5 hours. The beads were later transferred to a DI water sample and the transfer process was repeated every 30 minutes for another 2.5 hours. The samples were analyzed for lead concentrations to determine the AG bead (and AC) ability to adsorb and retain the lead. Table 11 shows the setup and results for this experiment, while Figure 26 shows the plotted results for both AG and AC.

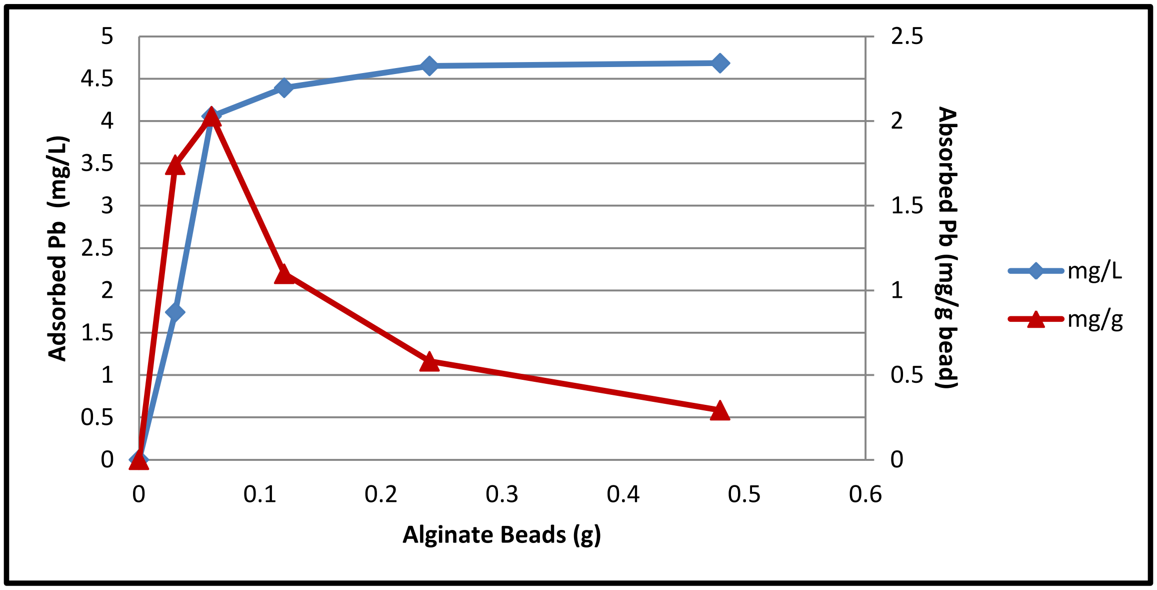



**Figure 25: AG sorption to 5 ppm lead solution**

**Table 11: Sorption-Desorption test setup and results**

| | | **Amount AG** | **Amount AC** |
|---|---|---|---|
| **Time (hrs)** | **Solutions** | 0.04 grams | 0.04 grams |
| **0.5** | Lead (5ppm) | 0.90 | 2.94 |
| **1** | Lead (5ppm) | 1.54 | 3.23 |
| **1.5** | Lead (5ppm) | 1.80 | 2.59 |
| **2** | Lead (5ppm) | 1.54 | 3.23 |
| **2.5** | Lead (5ppm) | 0 | 3.38 |
| **3** | DI water | 0 | 0 |
| **3.5** | DI water | 0 | 0 |
| **4** | DI water | 0 | 0 |
| **4.5** | DI water | 0 | 0 |
| **5** | DI water | 0 | 0 |

As can be observed in both Table 11 and Figure 26, AG achieved more adsorption at all times and no desorption was noted for either. This proves that AG innovation is more effective

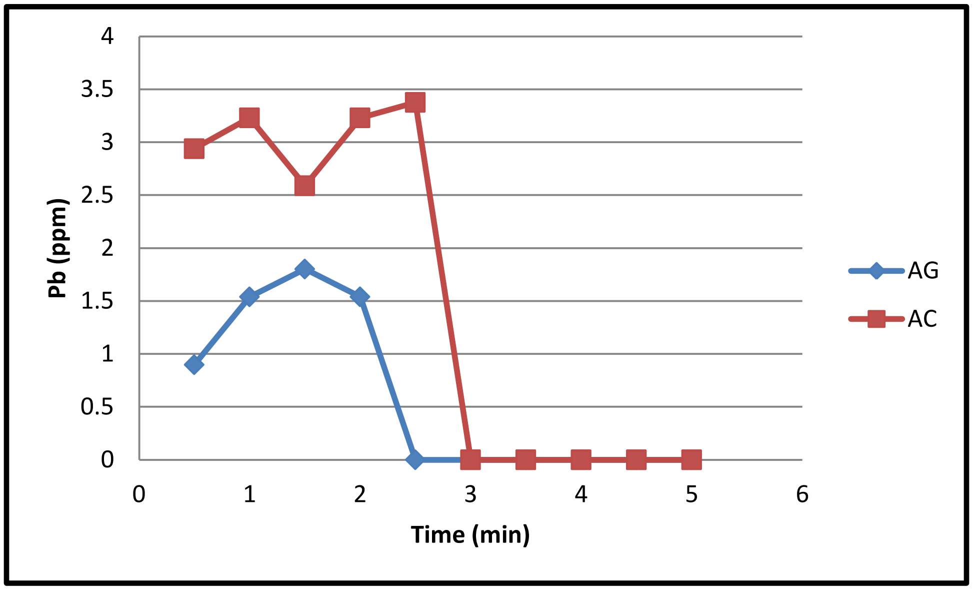



**Figure 26: Sorption-Desorption results for AG and AC**

Table 12 shows the result for AG and AC *E. coli* adsorption. Similar to the sorption-desorption test, AG beads excelled over AC by been able to reduce some *E. coli* concentrations at after 60 minutes of contact time while AC showed no reduction.

**Table 12: *E. coli* % reduction for AG and AC**

| Time | AC | AG |
|---|---|---|
| **30** | 125.81 | 0 |
| **60** | 112.90 | 48.39 |

When testing the filtering capabilities of the AG bead Table 13 was obtained. AG results show that the beads were able to reduce turbidity but increased COD, which could possibly be caused by initial bead leaching. In this particular case AC showed much better reduction in both turbidity, and COD. This can be explained by the form of the particles in each column. While beads are spherical shaped and equal in size, the AC particulate is amorphous and when packing it is compressed with its own weight reducing pore size causing more turbidity reduction. Note that the lead concentrations in both initial concentrations and effluent concentrations where under the detection limit (UDL) which is about 0.5ppm for the equipment used.

**Table 13: Filter column results for both AG and AC**

| Parameter | Units | Initial | AC | AG |
|---|---|---|---|---|
| **pH** | | 5.4 | 4.2 | 5.5 |
| **COD** | mg/L | 11.41 | 10.33 | 41.55 |
| **Conductivity** | µS/cm | 10.06 | 44.7 | 326 |
| **Turbidity**[1] | NTU | 4.58 | 1.65 | 3.13 |
| **Lead** | ppm | UDL | UDL | UDL |
| **Removed %** | | - | 63.97 | 31.66 |

Note: [1] Turbidity removal=$\frac{(Port1-Port3)}{Port\ 1} \times 100$

### 4.4. POE-CPU experiments

#### 4.4.1. POE-CPU runs

Three (3) experiments were done with the system with varying rainwater effluent conditions at a flow rate of 5 GPH. The next figures show the normalized results ($C/C_0$) for all three (3) experiments and their average. In the system (Figures 27-28), pH variations where minimal, ranging from 0.98 to 1.05. In most of the cases $C/C_0$ exceeded 1, which shows that the system increases the pH with respect to the initial value in the rainwater tank. This increase is expected and acceptable since pure rainwater tends to be acidic and it's desirable to acquire a final neutral pH of about 6-8. The average pH results showed a variance coefficient of less that 4% for the gravel effluent and less than 10% for the sand filter, which presents a low variance of the data (See Appendix D for normalized table). Considering COD variations in both gravel (Figure 29) and sand (Figure 30) filters, there were increases compared to initial value, which is of surprise since it is expected that the sand filter removes certain percent of the organic matter. Variance coefficients were high, from 63-85% for gravel samples and 2.8-40% for sand samples. These results show low reliability in the averaged results.

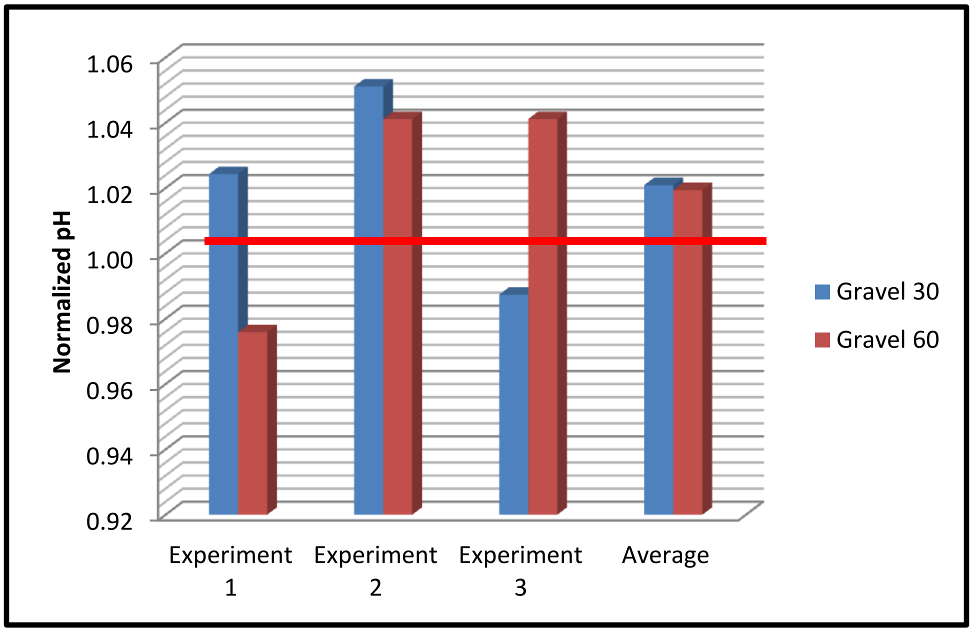



**Figure 27: pH variation in the gravel filter for all POE-CPU runs**

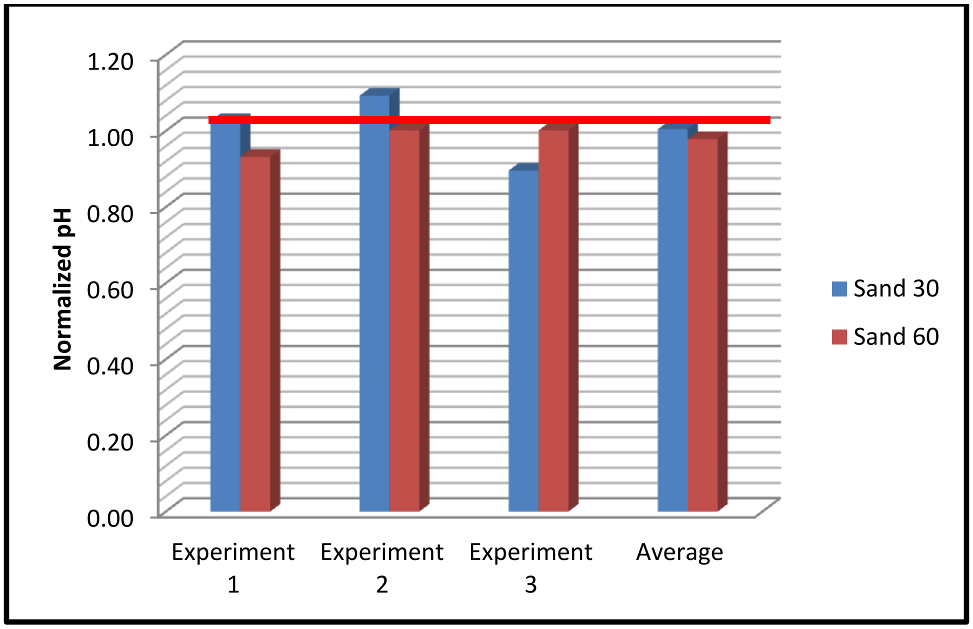



**Figure 28: pH variation in the sand filter for all POE-CPU runs**

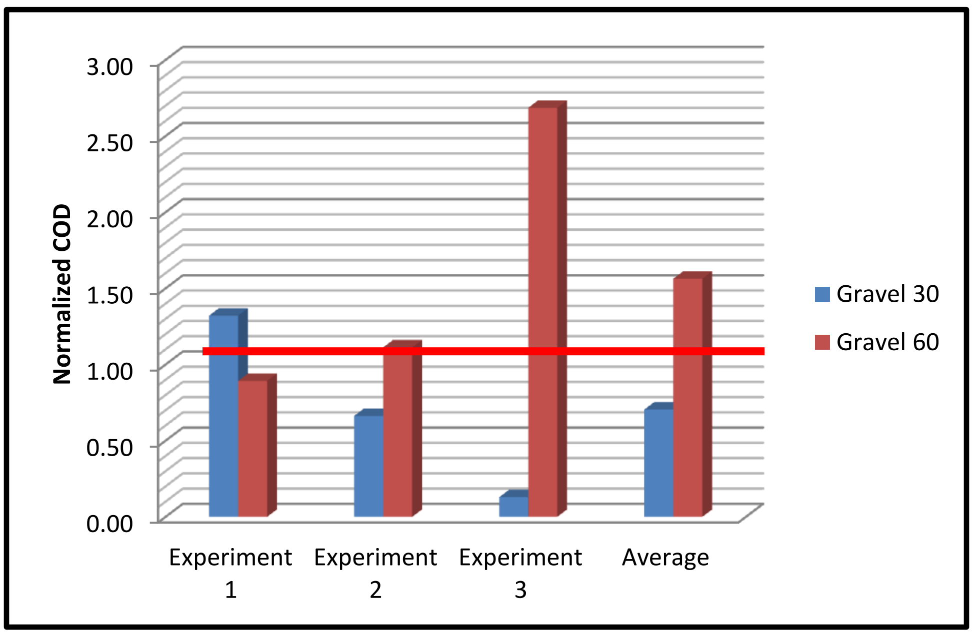
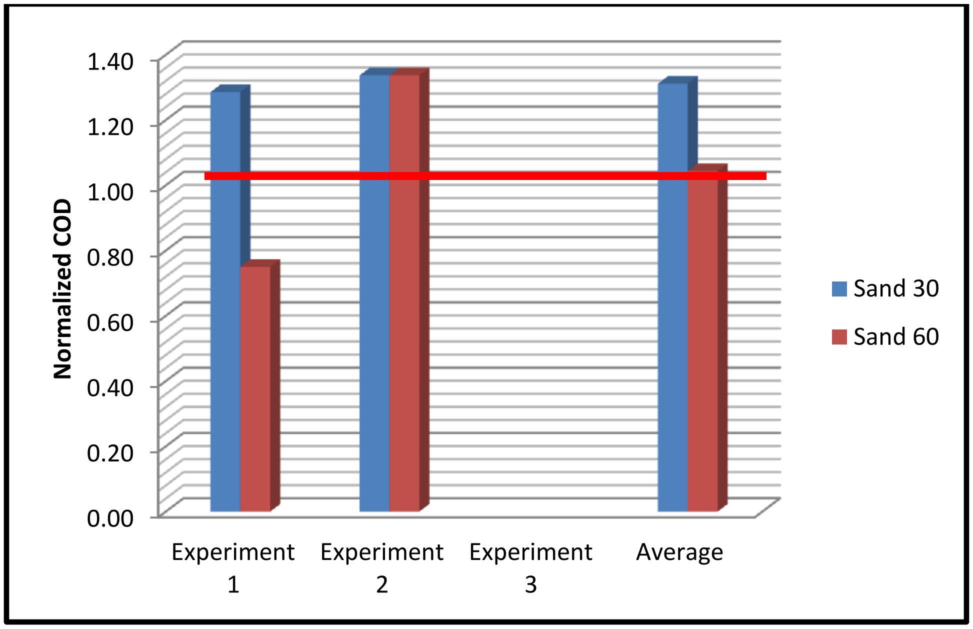


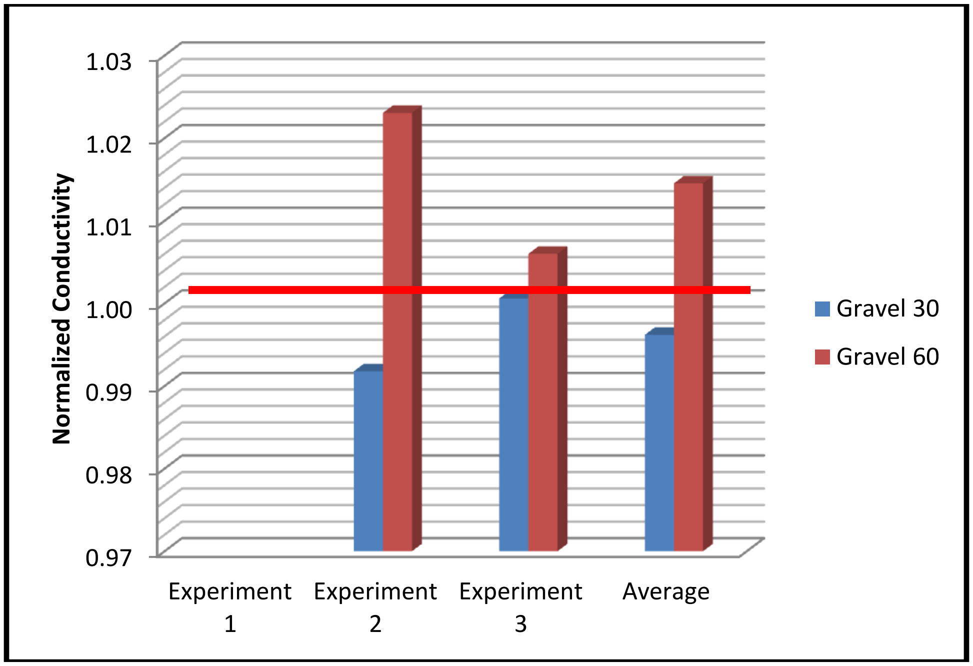

**Figure 29: COD variation in the gravel filter for all POE-CPU runs**




*Notes: Values from Experiment 3 were excluded since they were under the detection limit of the instrument utilized.

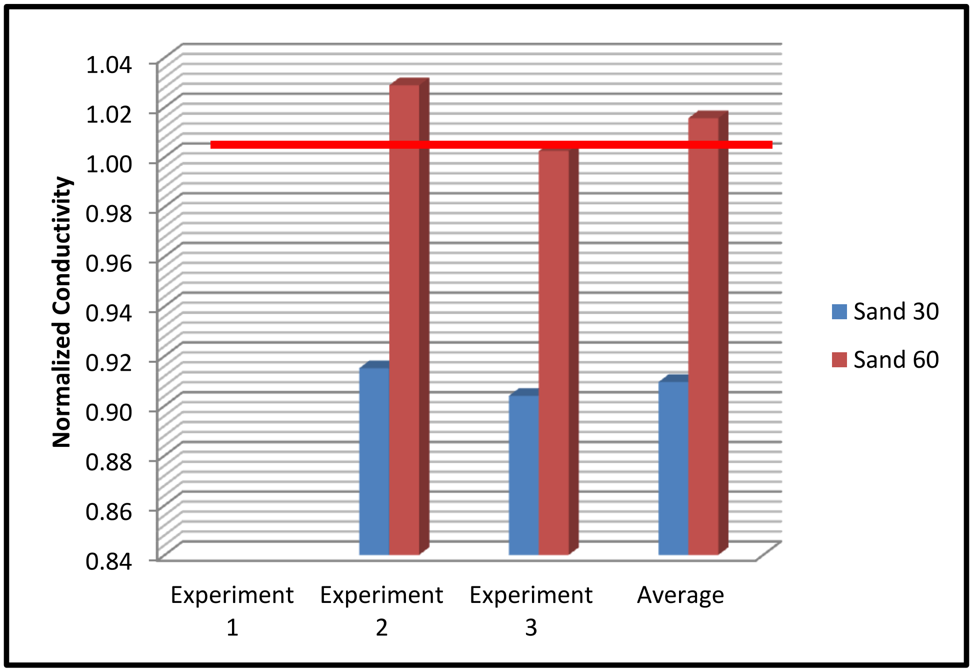
**Figure 30: COD variation in the sand filter for all POE-CPU runs**

Conductivity variations for both filters are shown in Figure 31 and Figure 32 and both show increases in the effluents conductivity. Variance coefficients were low, under 1.2% for gravel samples and under 1.8% for sand samples, which assure reliability when using averaged results. Results for turbidity variation are shown in Figure 33 and 34. As can be observed the gravel filter showed low removal (average~20%) while sand filter showed better performance (>40%). Variance coefficient for turbidity remained under 20% for gravel samples and under 32 % for sand samples.




*Notes: There are no conductivity values for experiment 1 since the equipment was malfunctioning

**Figure 31: Conductivity variation in the gravel filter for all POE-CPU runs**




*Notes: There are no conductivity values for experiment 1 since the equipment was malfunctioning

**Figure 32: Conductivity variation in the sand filter for all POE-CPU runs**

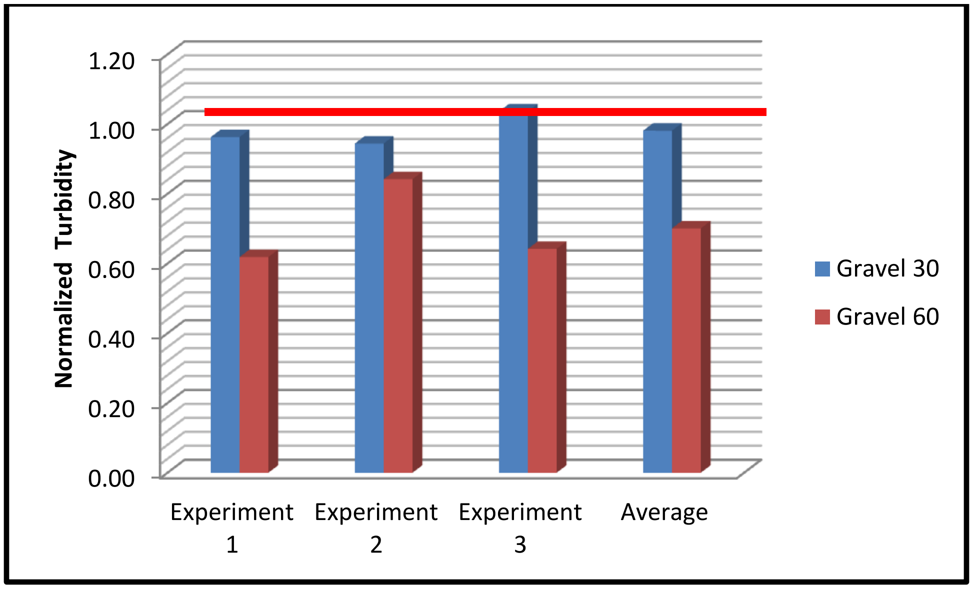



**Figure 33: Turbidity variation in the gravel filter for all POE-CPU runs**

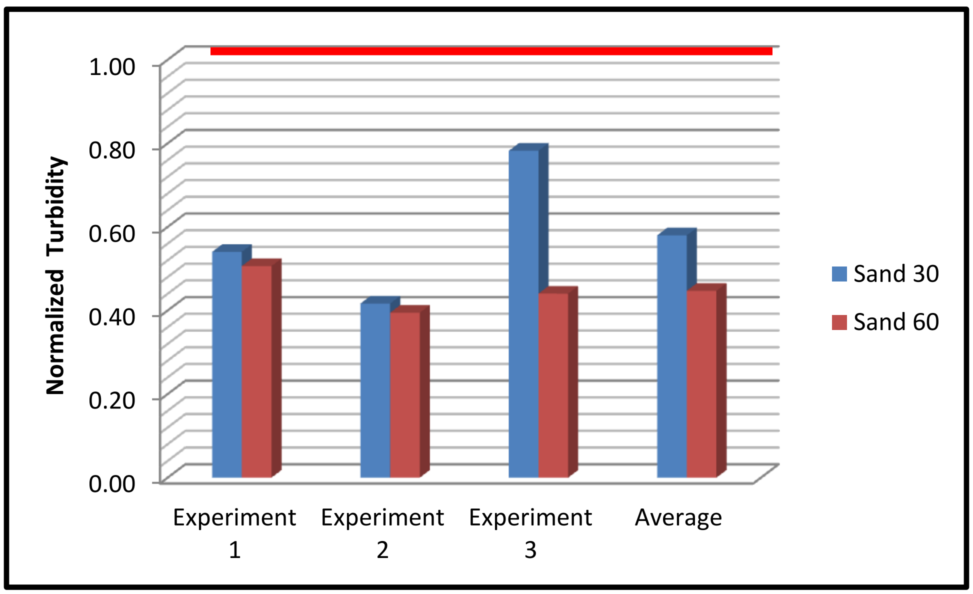



**Figure 34: Turbidity variation in the sand filter for all POE-CPU runs**

In order to determine system performance, relevant water quality results were tabulated and compared to USEPA standard regulations (Table 14). Quality parameters such as pH and chloroform concentrations were in compliance with regulations while turbidity and *E. coli* limit were exceeded. It is important to note that although *E. coli* regulation was exceeded, the amount of chlorine spiked achieved more than 99.99% removal (4-log removal) of initial concentrations.

Aspects to take in consideration from these results in order to improve effluent quality are:

- Reduce flow rate in order to improve turbidity reduction
- Monitor free chlorine in stock solution to improve *E. coli* inoculation in the system

To improve water quality in the effluent an addition of either activated carbon or calcium alginate beads was added to the sand filter. But first, we needed to determine the residence time in the POE-CPU. 50 grams of salt were added to the rainwater basin with 10 gallons of DI water and the system was run at 5 GPH. Every 2 minutes the conductivity was measured in both gravel and sand ports until it reached initial conductivity in the basin (2.3 mS/cm). Table 15 and Figure 31 shows residence time results.

**Table 14: POE-CPU run results comparison to USEPA standards (USEPA 2005, USEPA 2009)**

| Parameter | Units | 30 minutes | 60 minutes | Standard |
|---|---|---|---|---|
| **pH** | | 6.8 | 6.5 | 6-8 |
| **Turbidity**[a] | NTU | **3.30**[f] | **3.35**[f] | 1 |
| **Turbidity Removal**[b] | % | 33 | 56 | - |
| **$Cl_2$ spike** | mg/L | 49.37 | 4.06 | - |
| **$Cl_2$** | mg/L | **19.97**[f] | 0.48 | 4 |
| **Chloroform** | ppb | 69.5 | 5 | 80 |
| ***E. coli***[c,d] | CFU/100 mL | **3**[f] | **3**[f] | 0 |
| ***E. coli* Removal** [e] | % | 99.9999975 | 99.9999975 | - |
| **Log removal** | | > 5 | > 5 | - |

*Notes:

[a]Turbidity is taken from the sand filter, the rest of the parameters are taken from disinfection port

[b]Turbidity removal=$\frac{(Port1-Port3)}{Port\ 1} \times 100$

[c]DBP and *E. coli* samples only for RUN 2 and RUN 3

[d]For *E. coli* cultivation m-FC Broth ampoules were used

[e]*E. coli* removal= $\frac{(Port1-Port4)}{Port\ 1} \times 100$

[f]Red values show non-compliance with USEPA standards

**Table 15: Residence time in the POE-CPU at 5 GPH**

| | Conductivity (µS/cm) | |
|---|---|---|
| **Time (min)** | Gravel | Sand |
| **0** | 24.4 | 14.7 |
| **2** | 21.1 | 13.9 |
| **4** | 18.17 | 15.1 |
| **6** | 125.4 | 16.3 |
| **8** | 592 | 49.2 |
| **10** | 1149 | 132.7 |
| **12** | 1622 | 230 |
| **14** | 1910 | 319 |
| **16** | 2030 | 681 |
| **18** | 2020 | 860 |
| **20** | 1643 | 1063 |
| **22** | 1906 | 1288 |
| **24** | 1226 | 1438 |
| **26** | 2090 | 1642 |
| **28** | 2040 | 1800 |
| **30** | 2170 | 1015 |
| **32** | 2170 | 1960 |
| **34** | - | 2040 |
| **36** | 1667 | 2090 |
| **38** | 1206 | 2120 |
| **40** | 1991 | 2210 |
| **42** | 1969 | 1199 |

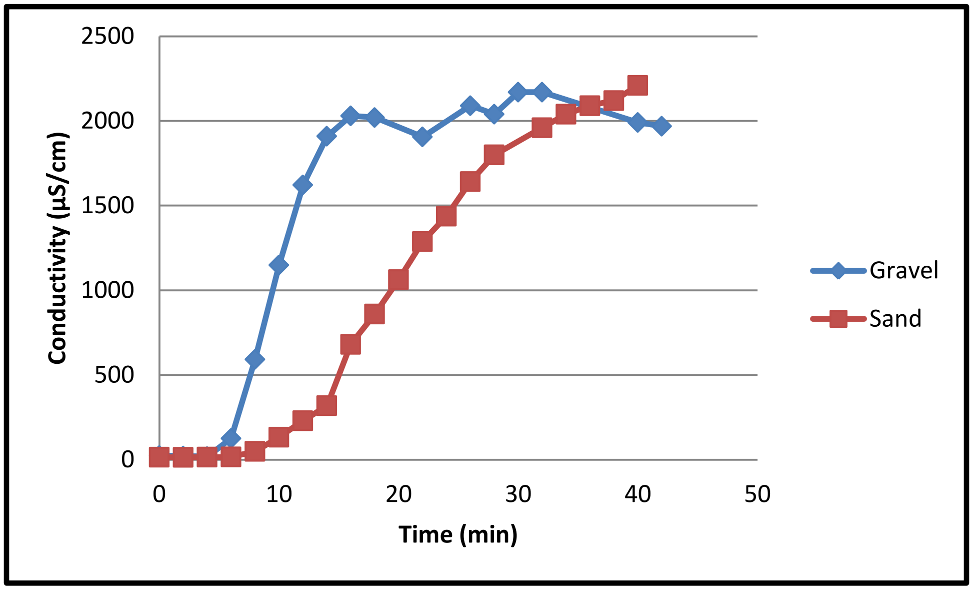



**Figure 35: Residence time plot for gravel and sand filters**

The results show 20 minutes of approximate residence time in the sand filter. In order to permit an acceptable contact time between AC or AG and the water it is desirable to increase it to at least 30 minutes. For the following experiments, especially those with heavy metal adsorption innovation, the optimum flow rate would be 3.25 GPH.

### 4.4.2. POE-CPU run with AC

A stocking containing approximately 150 grams of AC was placed a top of the sand bed and flow rate was adjusted again to 3.25 GPH. A total of three (3) experiments were done and the following figures show the normalized results ($C/C_0$) for all three (3) experiments and their average. Figures 36 and 37 show the variations on pH. In most cases, pH seemed to remain almost constant in both sample ports and showed variation coefficients under 11%. Similar to original POE-CPU runs most experiments showed increases in COD concentrations in the effluent from both filters while variance coefficients exceeded 65%, which again show low confidence in averaged results.

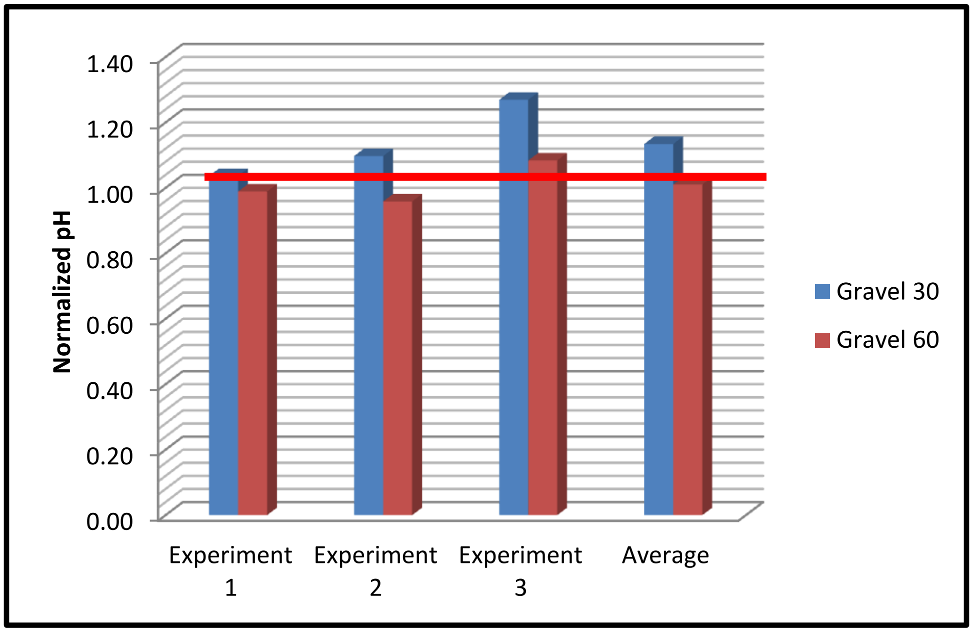



**Figure 36: pH variation in the gravel filter for all POE-CPU runs with AC**

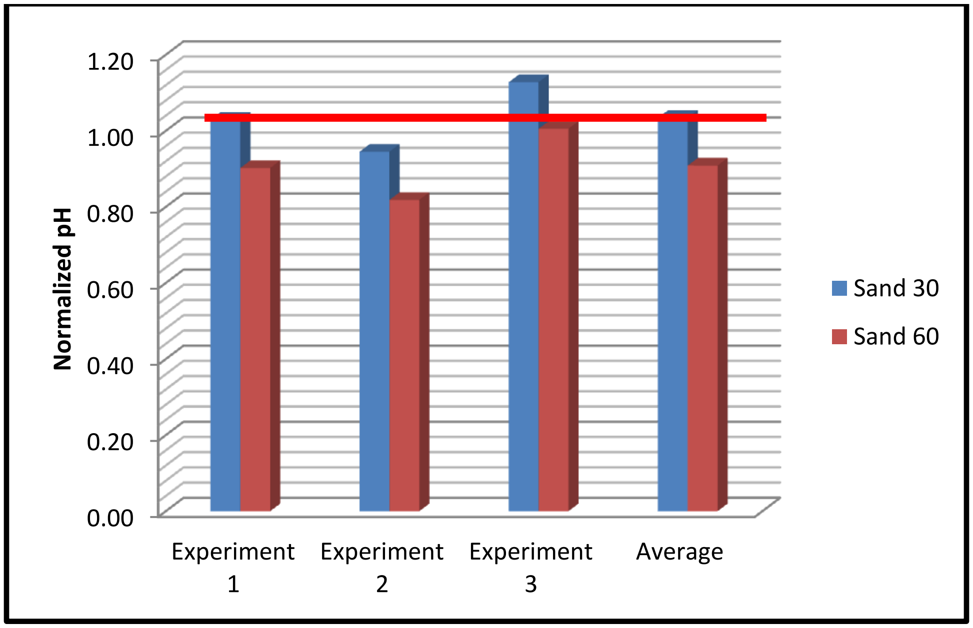



**Figure 37: pH variation in the sand filter for all POE-CPU runs with AC**

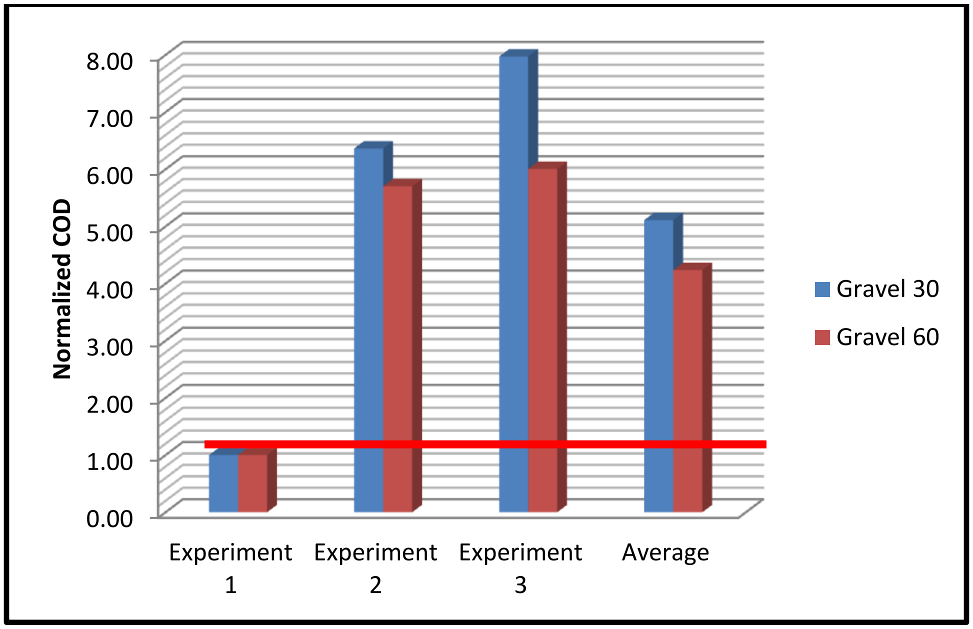



**Figure 38: COD variation in the gravel filter for all POE-CPU runs with AC**

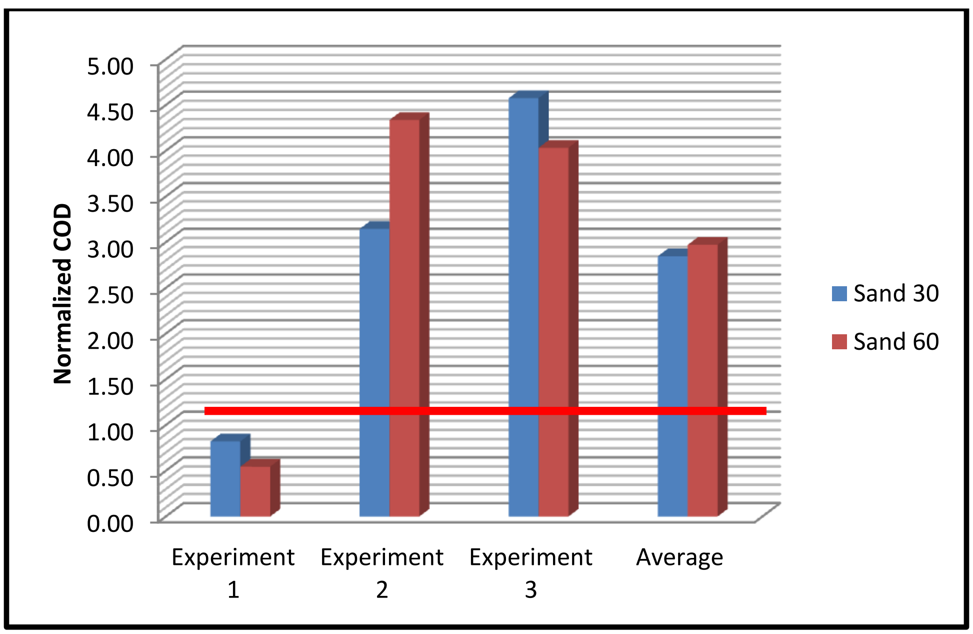



**Figure 39: COD variation in the sand filter for all POE-CPU runs with AC**

In the case of conductivity (Figures 40-41), results varied greatly from original experiments since most experiments showed a reduction in both filter effluents. Variance coefficient for gravel samples were high (100%) while sand results ranged from 54-90%. Figure 42 and 43 show all results for turbidity variations. Similar to the original runs, the gravel filter showed a removal of about 20% for all samples and about 40% for all sand samples. Variation coefficients for both filters remained under 5%.

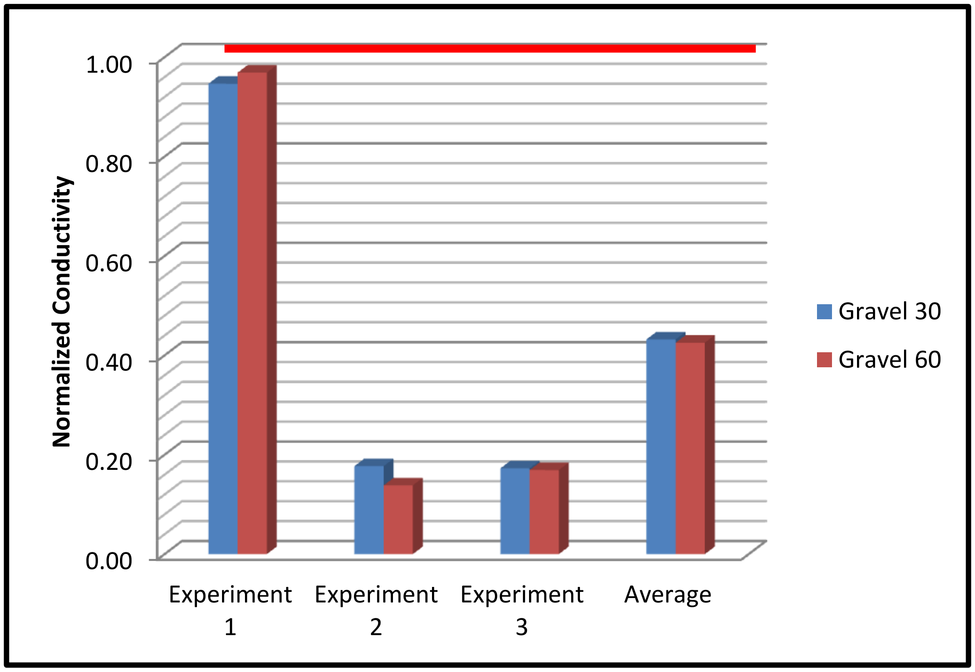



**Figure 40: Conductivity variation in the gravel filter for all POE-CPU runs with AC**

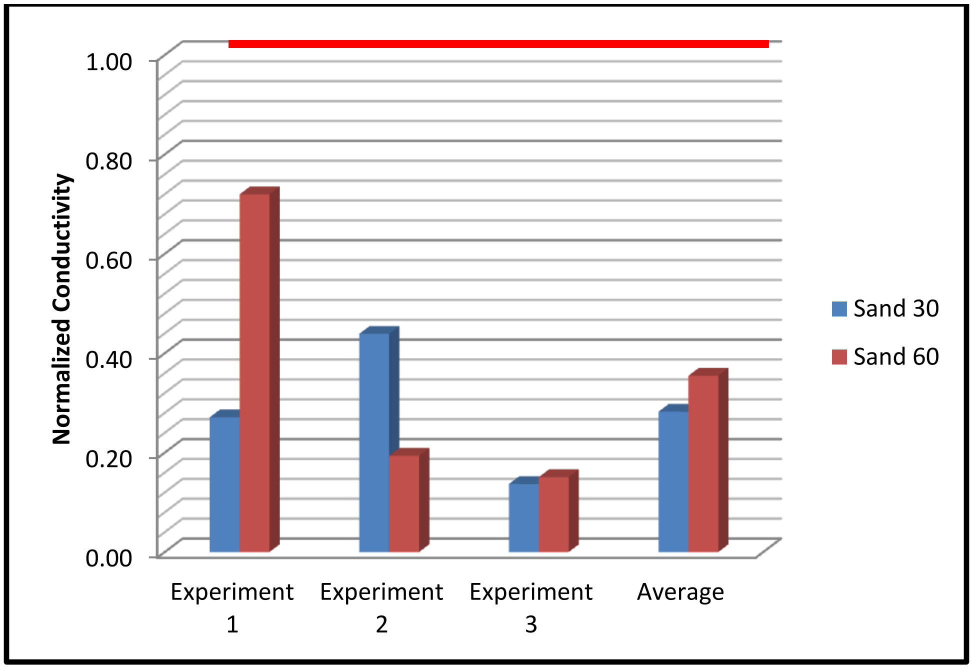



**Figure 41: Conductivity variation in the sand filter for all POE-CPU runs with AC**

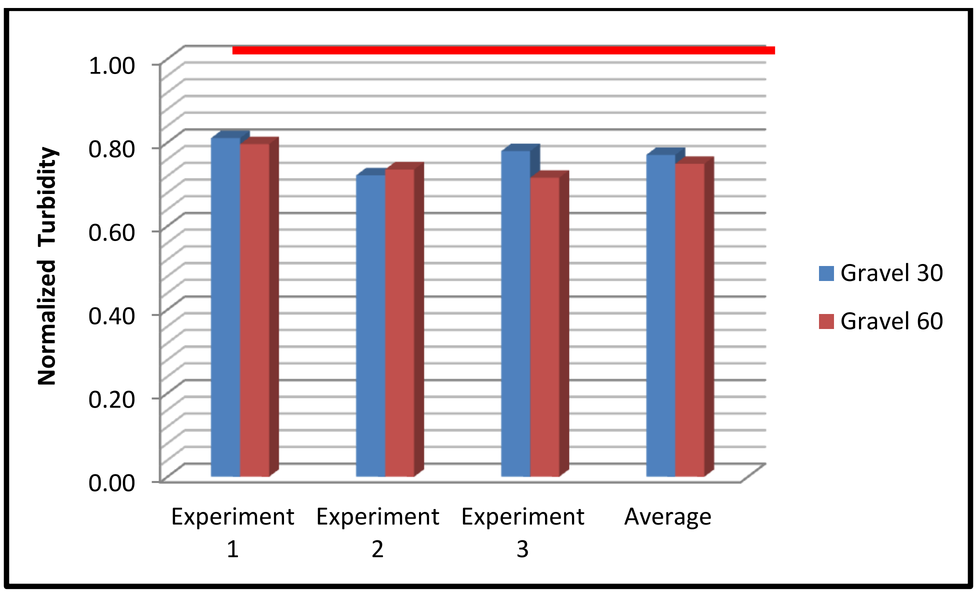



**Figure 42: Turbidity variation in the gravel filter for all POE-CPU runs with AC**

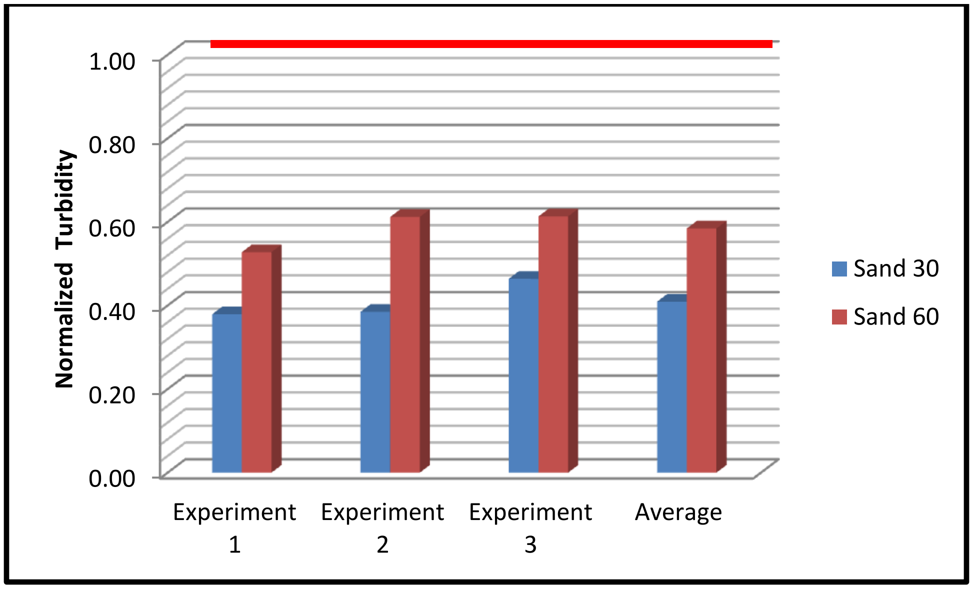



**Figure 43: Turbidity variation in the sand filter for all POE-CPU runs with AC**

Now when comparing with USEPA standards (Table 16), effluent turbidity exceeded (again) the 1 NTU regulation, but pH and chloroform where in compliance. In the case of *E. coli* presence, only in the averaged results from 30 minutes didn't comply, note again how the selected chlorine spike achieved more than 99.99% removal of the initial *E. coli* concentrations. Note that no lead concentrations were included in the results, this is because the results where under the detection limit of the equipment used.

**Table 16: POE-CPU run with AC results comparison with USEPA Standards (USEPA 2005, USEPA 2009)**

| Parameter | Units | 30 minutes | 60 minutes | EPA Standards |
|---|---|---|---|---|
| **pH** | | 7.3 | 7.2 | 6-8 |
| **Turbidity**[a] | NTU | **2.89**[d] | **4.44**[d] | 1 |
| **Turbidity Removal**[b] | % | 55 | 33 | - |
| **$Cl_2$ spike** | mg/L | 24.97 | 24.97 | - |
| **$Cl_2$** | mg/L | **11.4**[d] | **9.47**[d] | 4 |
| **Chloroform** | ppb | UDL [e] | UDL [e] | 80 |
| ***E. coli*** | CFU/100 mL | **1**[d] | 0 | 0 |
| ***E. coli* Removal** [c] | % | 99.99999545 | 100 | |
| **Log removal** | | > 5 | > 5 | |

*Notes:
[a]Turbidity is taken from the sand filter, the rest of the parameters are taken from disinfection port
[b]Turbidity removal=$\frac{(Port1-Port3)}{Port\ 1} \times 100$
[c]*E. coli* removal= $\frac{(Port1-Port4)}{Port\ 1} \times 100$
[d]Red values show non-compliance with USEPA standards
[e]UDL=under detection limit

### 4.4.3. POE-CPU run with AG

Another three (3) experiments were done with the system with the AG bead addition. A stocking containing approximately 100 grams of AG beads was placed a top of the sand bed and flow rate was adjusted again to 3.25 GPH. The next figures (Figure 44-51) show the normalized ($C/C_0$) water quality variation for all three (3) experiments and their average. pH variations are shown in Figures 44 and 45. In all samples a sligth increase of pH is detected in the effluent from both filters while the variance coefficient remains under 9%. Variations of COD differ greatly from previous experiments because they were slightly reduced in all samples. Another notable difference is the variance coefficient which remained under 10% with the exception of samples from the sand filter after 30 minutes.

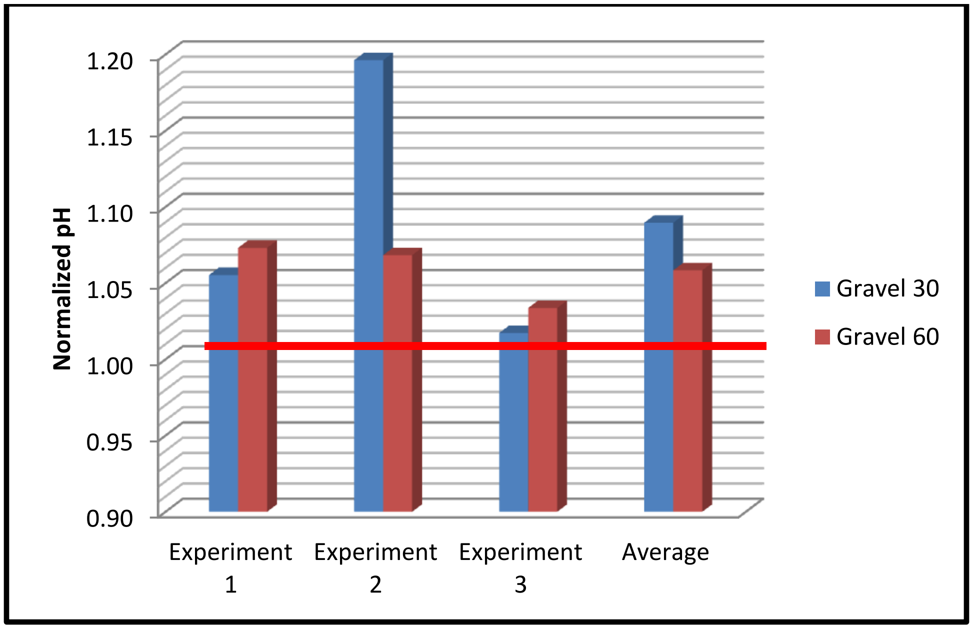



**Figure 44: pH variation in the gravel filter for all POE-CPU runs with AG**

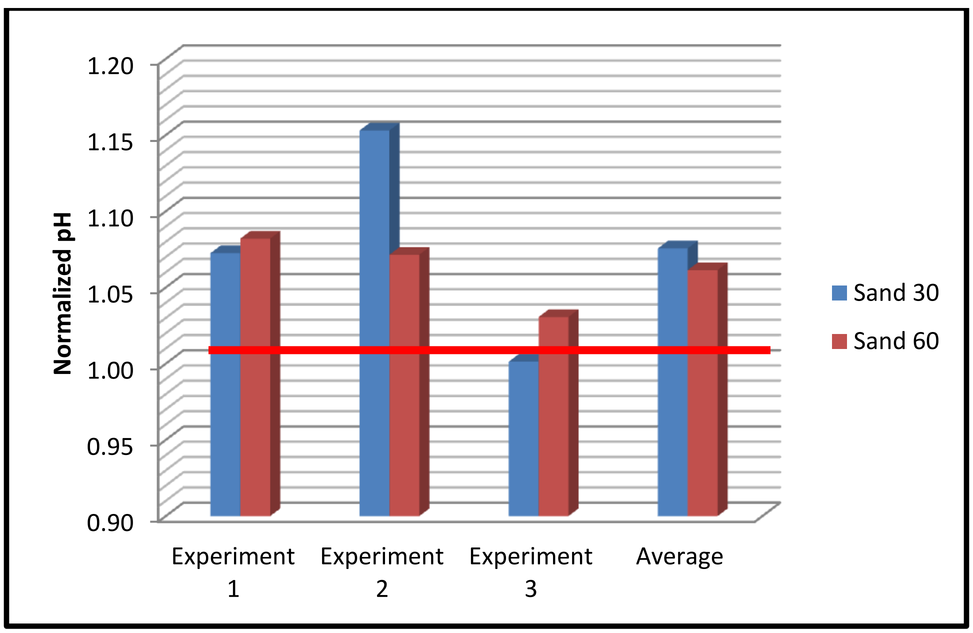



**Figure 45: pH variation in the sand filter for all POE-CPU runs with AG**

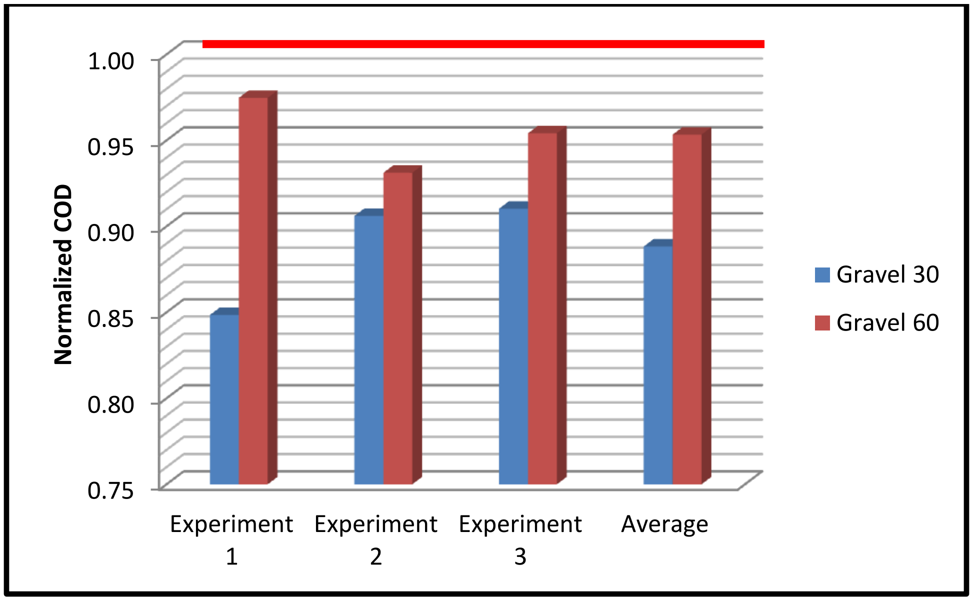



**Figure 46: COD variation in the gravel filter for all POE-CPU runs with AG**

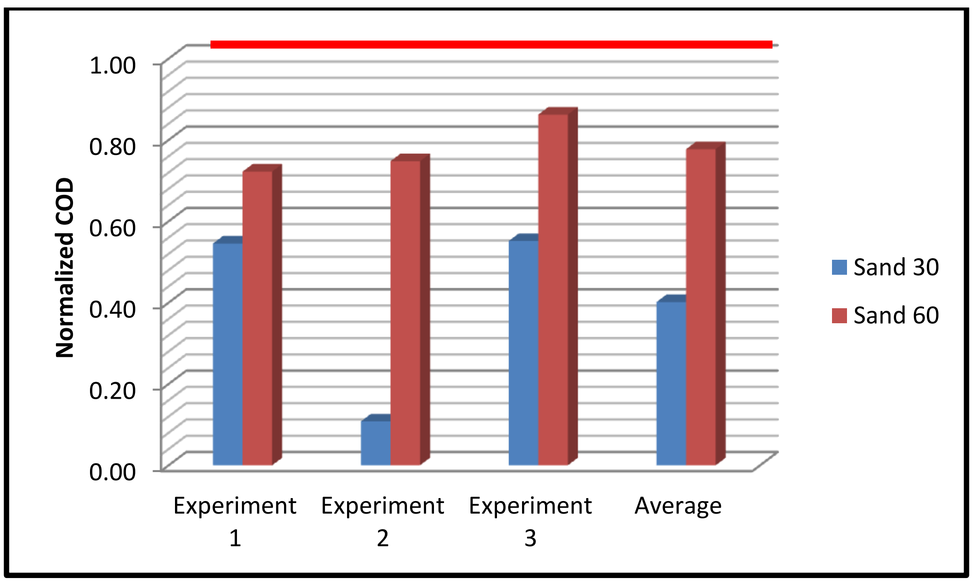



**Figure 47: COD variation in the sand filter for all POE-CPU runs with AG**

In the case of conductivity variations (Figures 48 and 49) all samples from the gravel filter showed increases while their averaged results remained under 13% (Figure 48). For sand samples (Figure 49) most samples showed increase in the conductivity but variance coefficient was considerably higher than gravel samples (16-70%). Meanwhile, turbidity variation results are shown in Figures 50 and 51. For gravel samples (Figure 50), turbidity removal varied from 14 -37% but variance coefficients remained under 17%. In the case of sand samples (Figure 51), removal performance varied from 30-69%, which caused the variance coefficient to increase to about 26%.

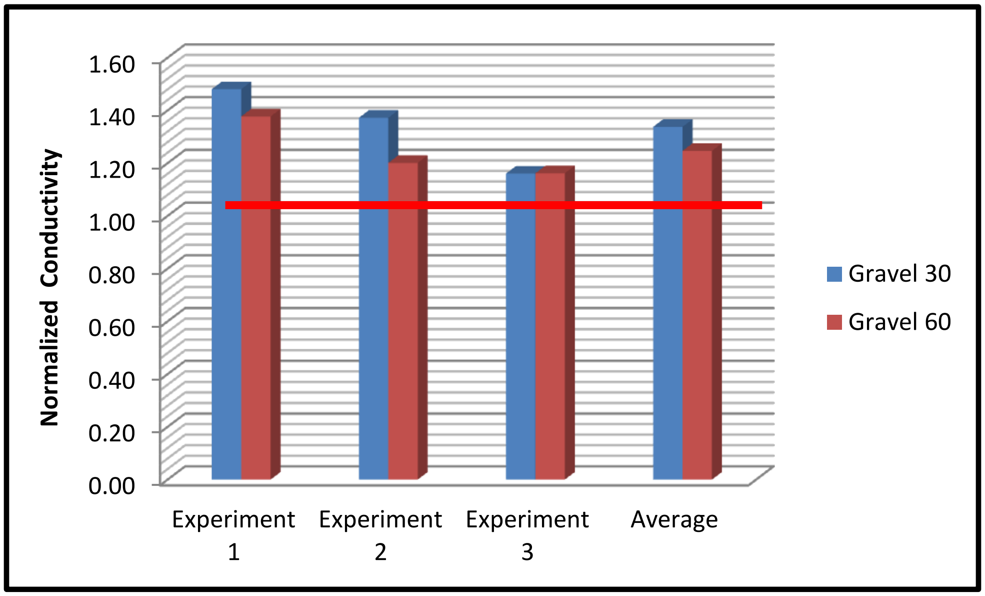



**Figure 48: Conductivity variation in the gravel filter for all POE-CPU runs with AG**

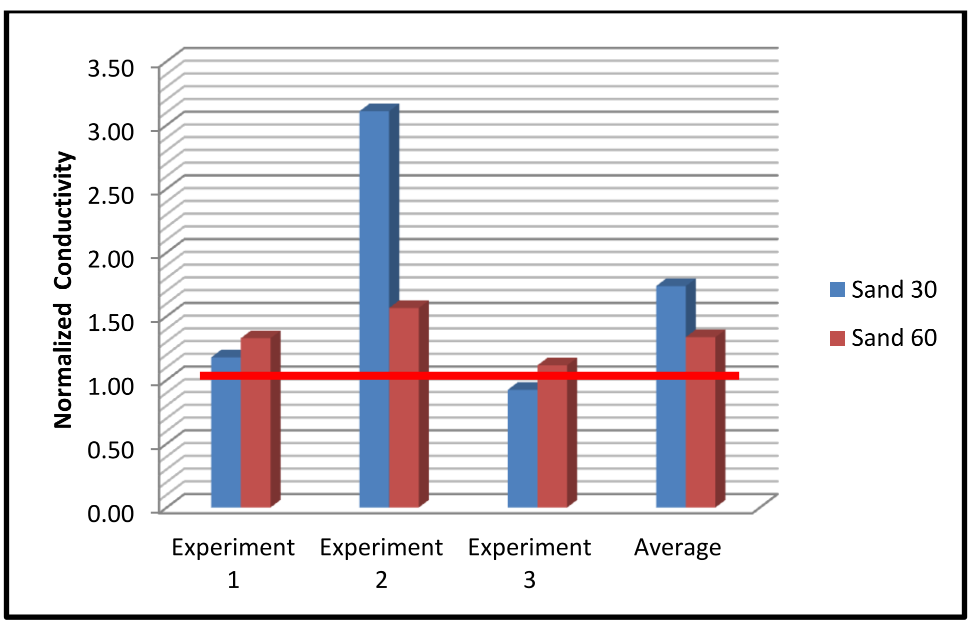



**Figure 49: Conductivity variation in the sand filter for all POE-CPU runs with AG**

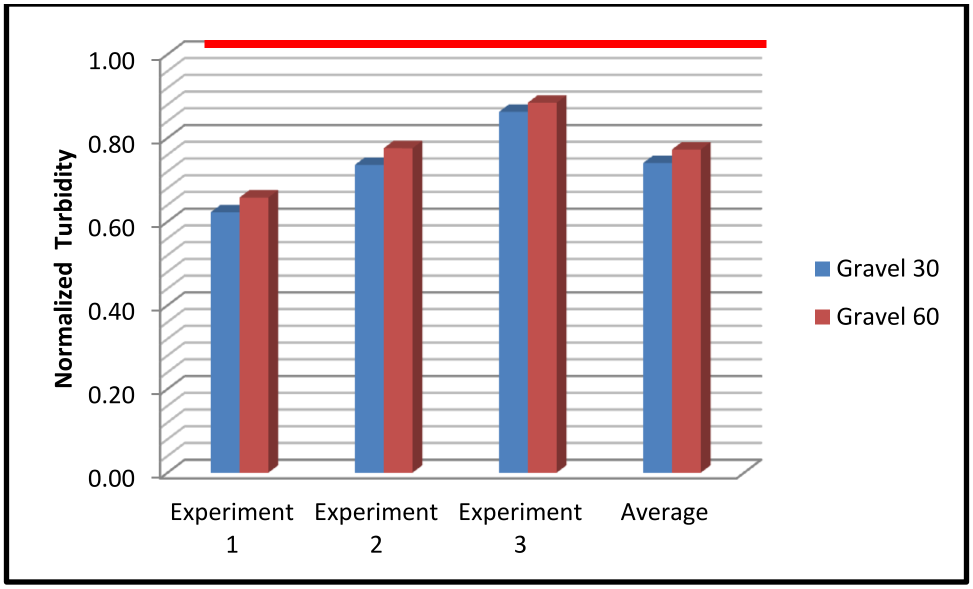



**Figure 50: Turbidity variation in the gravel filter for all POE-CPU runs with AG**

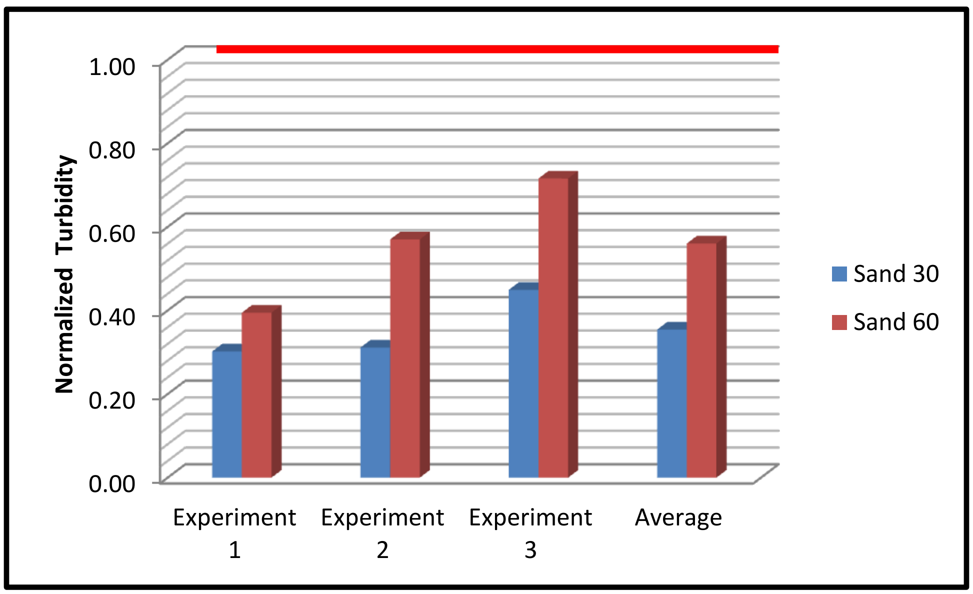



**Figure 51: Turbidity variation in the sand filter for all POE-CPU runs with AG**

When comparing effluent water quality to USEPA standards we achieve compliance at both time samples for pH and chloroform, while turbidity and free chlorine concentration were exceeded (Table 17). Microbial results showed compliance only in 60 minute samples, but a removal of 99.99% was achieved. Note again that no lead concentrations were included in the results, this is because the results where under the detection limit of the equipment used.

**Table 17: POE-CPU run with AG results comparison with USEPA Standards (USEPA, 2005; USEPA, 2009)**

| Parameter | Units | 30 minutes | 60 minutes | Standards |
|---|---|---|---|---|
| **pH** | | 7.7 | 7.5 | 6-8 |
| **Turbidity**[a] | NTU | **3.32**[d] | **5.46**[d] | 1 |
| **Turbidity Removal**[b] | % | 65 | 45 | - |
| **$Cl_2$ spike** | mg/L | 13.4 | 13.4 | - |
| **$Cl_2$** | mg/L | **8.95**[d] | **7.65**[d] | 4 |
| **Chloroform** | ppb | UDL[e] | UDL[e] | 80 |
| ***E. coli*** | CFU/100 mL | **1**[d] | 0 | 0 |
| ***E. coli* Removal** [c] | % | 99.9999975 | 99.9999975 | |
| **Log removal** | | > 5 | > 5 | |

*Notes:

Turbidity is taken from the sand filter, the rest of the parameters are taken from disinfection port

[2]Turbidity removal=$\frac{(Port1-Port3)}{Port\ 1} \times 100$

[3]*E. coli* removal= $\frac{(Port1-Port4)}{Port\ 1} \times 100$

[4]Red values show non-compliance with USEPA standards

[e]UDL=under detection limit

### 4.4.4. Comparison between treatments

In order to determine best treatment for harvested rainwater the results from each treatment were averaged and are shown in the following figures. From Figure 52, we see that both POE-CPU and POE-CPU with AG slightly increased pH in the sand effluent while POE-CPU with AC showed slight reduction. In terms of variance coefficient, POE-CPU with AG showed more reliable data dispersion with a value of ~5%, while POE-CPU and POE-CPU with AC showed 7% and 11%, respectively. When considering COD variations (Figure 53) both initial treatment and treatment with AC showed increases in concentrations while treatment with AG showed removal of about 40%.

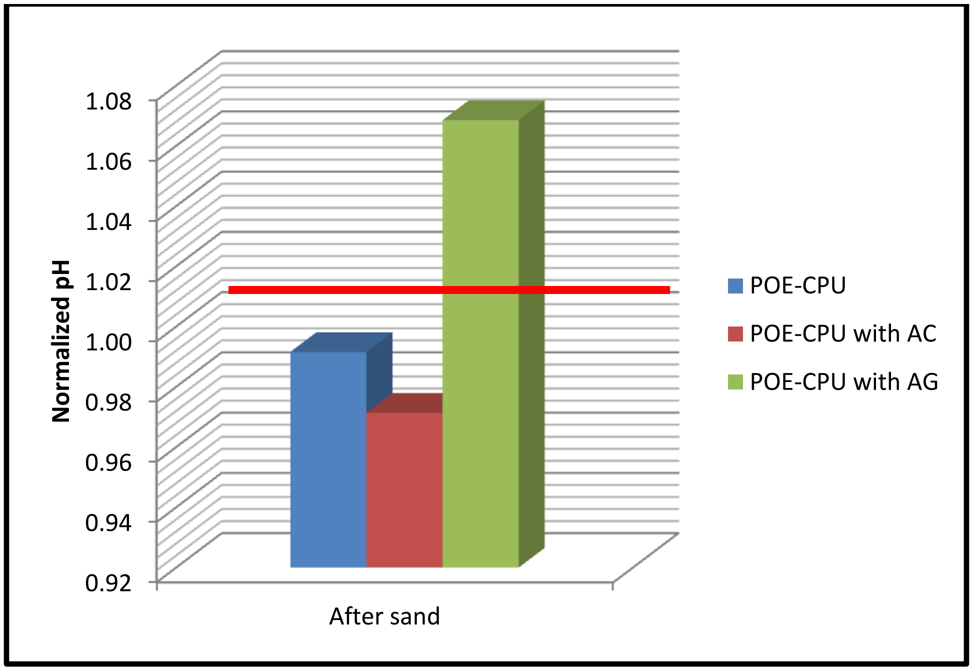



**Figure 52: pH variation comparison between treatments**

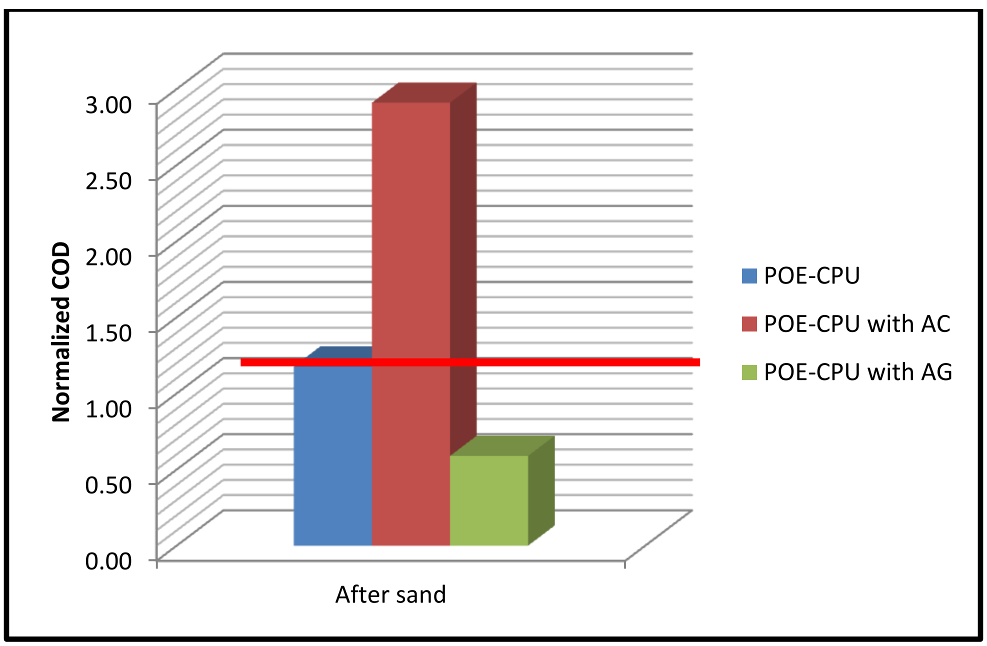



**Figure 53: COD variation comparison between treatments**

Now considering conductivity (Figure 54), both POE-CPU and POE-CPU with AC showed reduction while POE-CPU with AG showed an increase in concentrations which could be due to bead leaching. If we consider reliability of averaged results, only POE-CPU showed low variance coefficient (6.5%) while POE-CPU with AC and POE-CPU with AG showed values over 50%. Finally, comparing turbidity results in Figure 55, an average removal of 48%, 51% and 55% was achieved for initial treatment, AC treatment and AG treatment, respectively. Variance coefficient for all treatments remains under 36%.

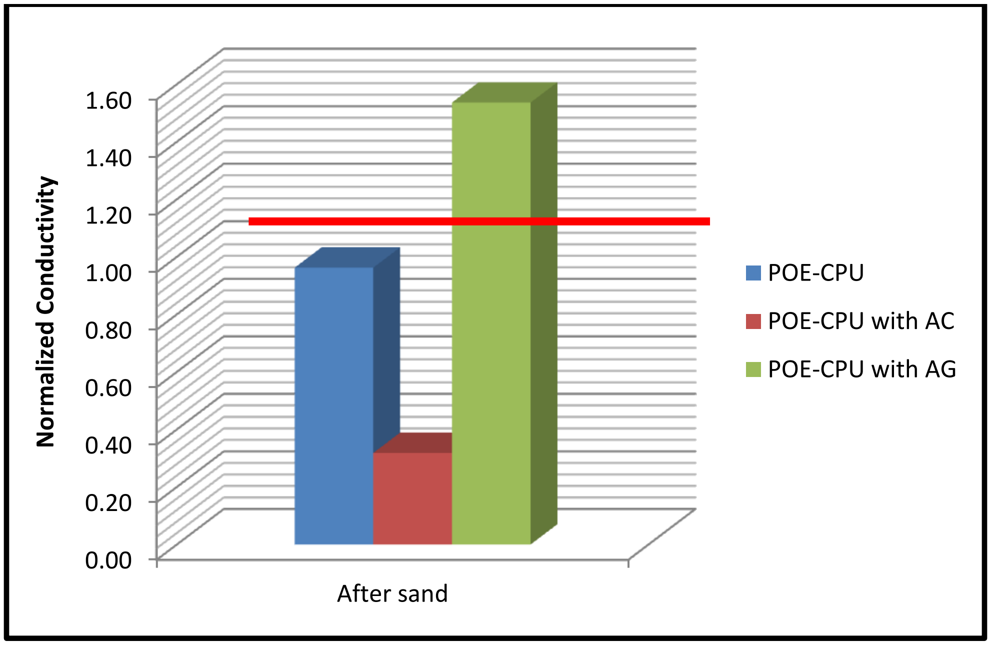



**Figure 54: Conductivity variation comparison between treatments**

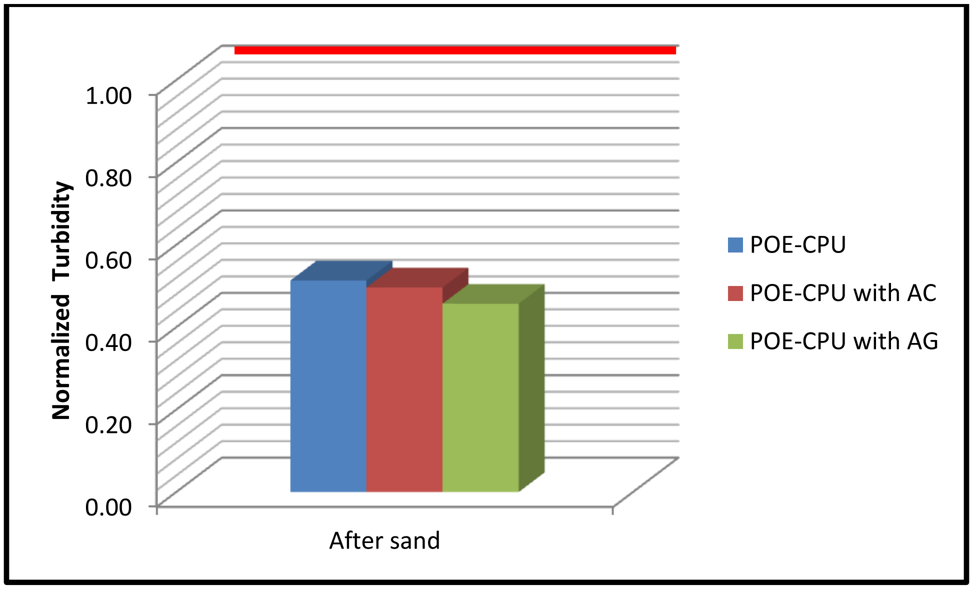



**Figure 55: Turbidity variation comparison between treatments**

Table 18 shows the comparison between treatment effluent and USEPA Standards. All values marked in red show non compliance with the established regulations. As can be observed all treatments complied with chloroform concentrations and pH secondary regulations, but exceeded both turbidity and residual chlorine concentrations. *E. coli* was present in all three disinfection samples, but to an extremely low degree. In general terms a conclusion can be made that the POE-CPU with the addition of AG beads is the best option for rainwater treatment since it achieved higher removal rates for turbidity and *E. coli*, while complying with chloroform and pH regulations.

**Table 18: POE-CPU treatment comparison with USEPA Standards (USEPA, 2005; USEPA, 2009)**

| Parameter | Units | POE-CPU | POE-CPU with AC | POE-CPU with AG | USEPA Standards |
|---|---|---|---|---|---|
| **pH** | | 6.6 | 7.2 | 7.6 | 6-8 |
| **Turbidity**[a] | NTU | **3.33**[d] | **3.67**[d] | **4.39**[d] | 1 |
| **Turbidity Removal**[b] | % | 44.5 | 44 | 55 | - |
| **$Cl_2$ spike** | mg/L | 26.72 | 24.97 | 13.4 | - |
| **$Cl_2$** | mg/L | **10.23**[d] | **10.43**[d] | **8.3**[d] | 4 |
| **Chloroform** | ppb | 37.25 | UDL[e] | UDL[e] | 80 |
| ***E. coli*** | CFU/100 mL | **3**[d] | **1**[d] | **1**[d] | 0 |
| ***E. coli* Removal** [c] | % | 99.9999975 | 99.9999986 | 99.99999987 | - |
| **Log removal** | | > 5 | > 5 | > 5 | - |

*Notes:

[a]Turbidity is taken from the sand filter, the rest of the parameters are taken from disinfection port

[b]Turbidity removal=$\frac{(Port1-Port3)}{Port\ 1} \times 100$

[c]*E. coli* removal=$\frac{(Port1-Port4)}{Port\ 1} \times 100$

[d]Red values show non-compliance with USEPA standards

[e] UDL=under detection limit

A final comparison between the treatments can be made by considering rainwater quality variation. Table 19 shows the rainwater quality variation from all collected samples[6]

**Table 19: Rainwater quality variation**

| | Min | Average | Max | 25 Percentile | 75 Percentile |
|---|---|---|---|---|---|
| **Ph** | 5.2 | 6.1 | 7.5 | 5.4 | 6.6 |
| **Conductivity µ** | 3.18 | 27.46 | 62.21 | 16.36 | 32.4 |
| **Temperature (°C)** | 25 | 25 | 25 | 25 | 25 |
| **COD (mg/L COD)** | -1 | 17.20 | 75 | 3.51 | 22.24 |
| **E-coli (CFU/ 100 mL)** | 5100 | $3.8 \times 10^8$ | $1.5 \times 10^9$ | $1.6 \times 10^5$ | $3.8 \times 10^8$ |
| **Turbidity (NTU)** | 0.68 | 2.64 | 6.90 | 1.22 | 3.21 |

By applying the percent removal calculated in Table 18, we can estimate how the treatments would behave with the quality variation in parameters of major concern (turbidity and

[6] See appendix for complete data

*E. coli*). Tables 20 and 21 shows the expected water quality results from all treatments by applying the percent removal obtained in Table 18.

**Table 20: Estimation of turbidity results for all treatments (USEPA, 2005; USEPA, 2009)**

| Turbidity (NTU) | POE-CPU | POE-CPU with AC | POE-CPU with AG | USEPA Standard |
|---|---|---|---|---|
| **Minimum** | 0.38 | 0.38 | 0.31 | 1 |
| **25%** | 0.68 | 0.68 | 0.55 | 1 |
| **Average** | **1.47** | **1.48** | **1.19** | 1 |
| **75 %** | **1.78** | **1.80** | **1.44** | 1 |
| **Maximum** | **3.83** | **3.86** | **3.11** | 1 |

**Table 21: *E. coli* estimation results from all treatments (USEPA, 2005; USEPA, 2009)**

| *E. coli* (CFU/100 mL) | POE-CPU | POE-CPU with AC | POE-CPU with AG | Standard |
|---|---|---|---|---|
| **Minimum** | $1.3 \times 10^{-4}$ | $7.1 \times 10^{-5}$ | $6.6 \times 10^{-6}$ | 0 |
| **25%** | $4.1 \times 10^{-4}$ | $2.3 \times 10^{-4}$ | $2.1 \times 10^{-5}$ | 0 |
| **Average** | **9.4** | **5.3** | $4.9 \times 10^{-1}$ | 0 |
| **75 %** | **9.4** | **5.3** | $4.9 \times 10^{-1}$ | 0 |
| **Maximum** | **37.5** | **21** | **2** | 0 |

As can be observed (Table 20), compliance of turbidity limits would only be reached when influent turbidity is less than 2.5 NTU for all treatments. Concerning *E .coli* removal (Table 21), AG treatment would comply with at least the 75% of the collected water, while original and AC treatment would have exceeded the standard.

# 5. CONCLUSIONS AND RECOMMENDATIONS

Scarcity and pollution of water supplies are a reality that the world currently faces and as time passes the situation grows bleaker. The utilization of rainwater provides a sustainable and cleaner water supply that can be made potable with minimal treatment. When rainwater is desired for potable uses, the POE-CPU may present a solution with many advantages. One of these advantages, is that it uses a very accessible and technically inexpensive water supply, that can be collected in the house or building rooftop. Another advantage is that the materials used for the filtration are relatively cheap and commercially available. Both gravel and sand media can be purchased from Sand and Silica Co. at about $30 per 20 kg of material, while AG beads can be purchased from Acros Organics at $50 per 250 grams. Because of its simplicity, the POE-CPU requires minimal maintenance and an easy to learn skill set to operate. As far as cleanup for this system is concerned, the gravel filter can be cleaned by moving the media and flushing the filter with tap water. On the other hand, because the sand filter is considered to be slow sand filtration, it is only needed to scrape the top of the filter to remove some of the bio-film that is formed with constant use, and flush it with tap water afterwards. A very significant advantage of the POE-CPU is that it requires less energy to operate than traditional systems since it is intended to be connected to roof spouts, so the water will move by gravity and it will only need a single pump to push the water to the storage unit.

When considering the effects of the POE-CPU regarding water quality, it can be observed that it is able to regulate rainwater acidic pH resulting in compliance with the USEPA Secondary Standards. With the studied sand filter design, the POE-CPU removes up to 44% turbidity at 5 GPH without any additives and 55% when innovated with calcium alginate beads at 3.25 GPH. In most cases, the POE-CPU achieves more than 4-log removal of *E. coli* when adding 0.1 mL of

1% sodium hypochlorite solution per 100 mL of water and uses commercial cleaner (bleach) as disinfectant, which can be found at many local retailers.

As presented, the system is currently recommended as a supplementary unit for locations with traditional water treatment systems and indispensable for improving water quality for locations that use raw rainwater as a supply source. In order to improve and adapt the POE-CPU to any desired conditions the following considerations and alterations are recommended:

- A study of rainwater occurrence and intensity is recommended to verify if installing the system would be viable and cost effective.
- Regular rooftop cleanup is recommended since it would greatly improve POE-CPU effluent water quality.
- Depending on desired use and need, augmenting filter dimensions, while keeping sand distribution (25% coarse, 50% medium, 25% fine), will help in increasing treated water volume.
- If household location is in an area where there are no trees in the vicinity, consider eliminating and/or bypassing gravel pre-filter, since removal of small particles is achieved only by the sand filter.
- Consider replacing liquid disinfectant with chlorine tablets, which will make system management and maintenance simpler and easier.

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# APPENDIX

**A. *E. coli* inoculation**

The following figures show both residual free chlorine and CFU variation for all four (4) inoculation experiments, including a fifth experiment made for the purpose of observing the *E. coli* bacteria variation in reactor 2 which contained no chlorine.

## A.1. First experiment

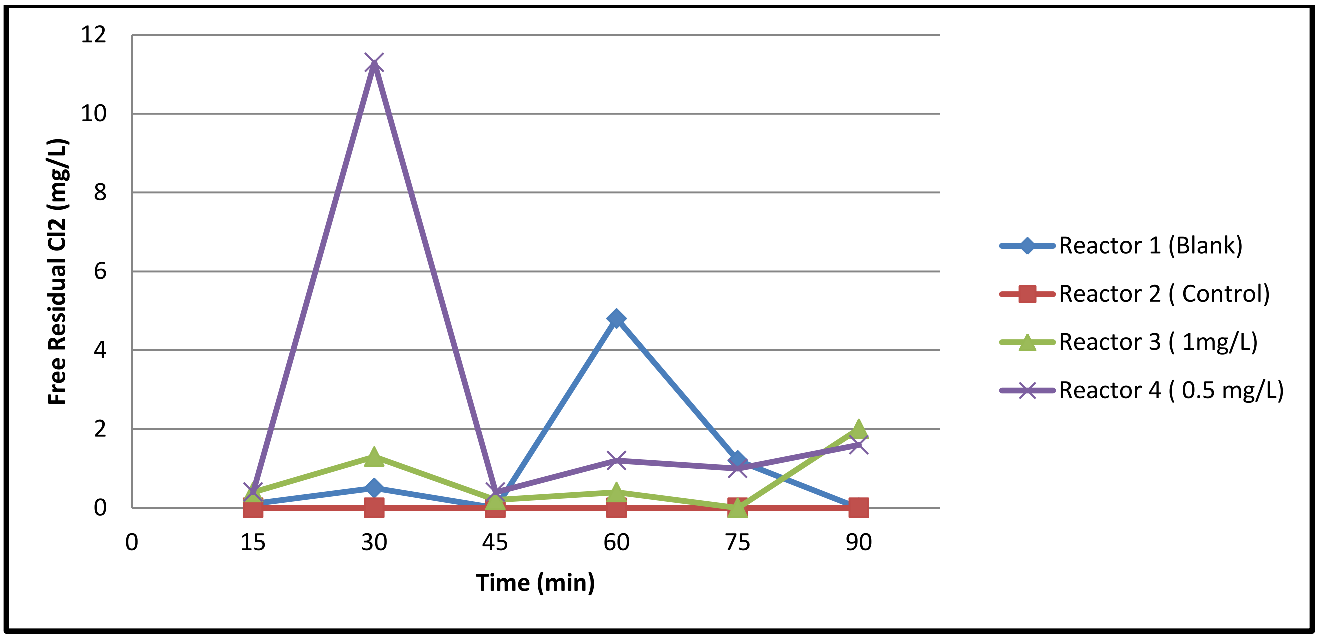



**Figure 56: Free residual chlorine concentration for 1st experiment**

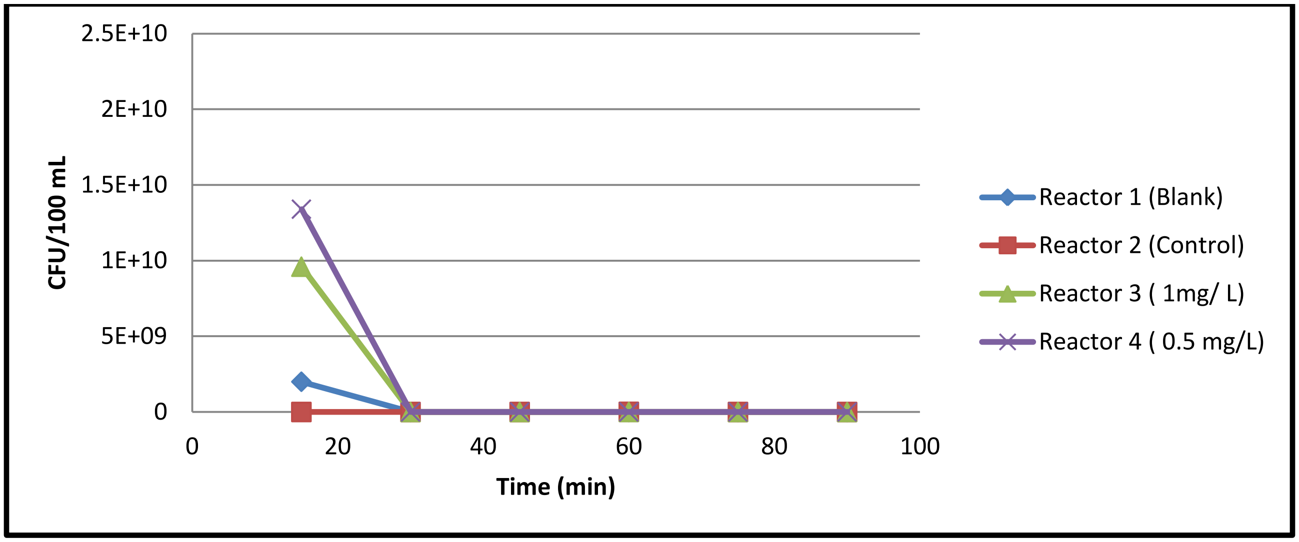



**Figure 57: CFU variation for *E. coli* inoculation in 1st experiment**

## A.2. Second experiment

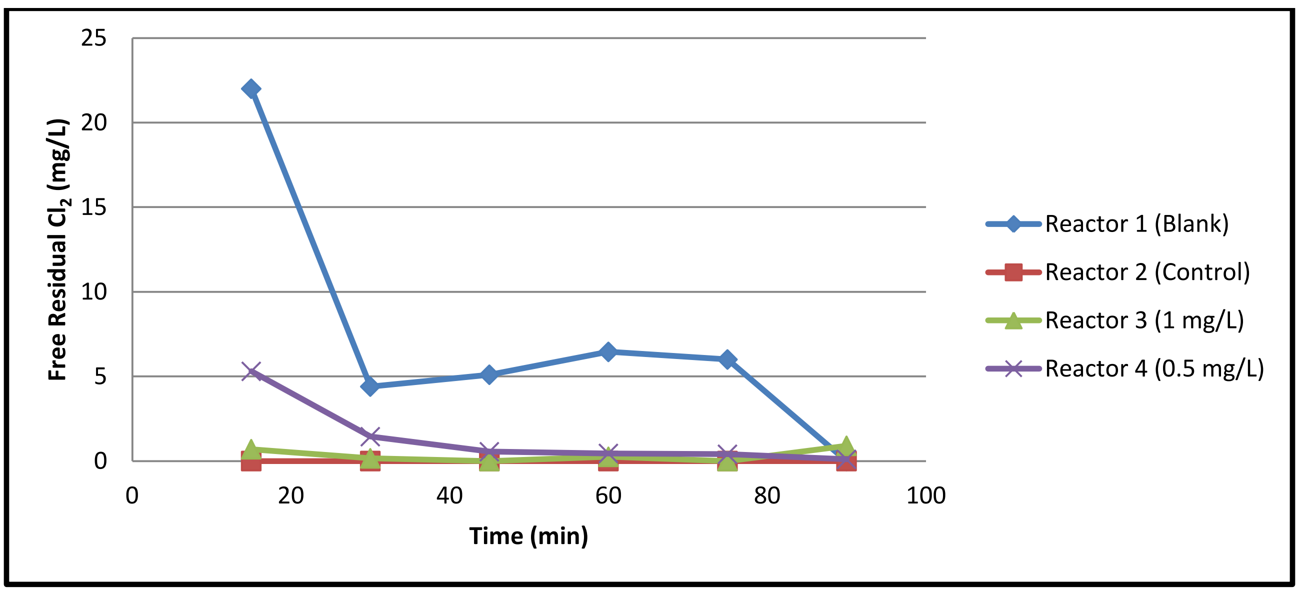



**Figure 58: Free residual chlorine concentration in 2nd experiment**

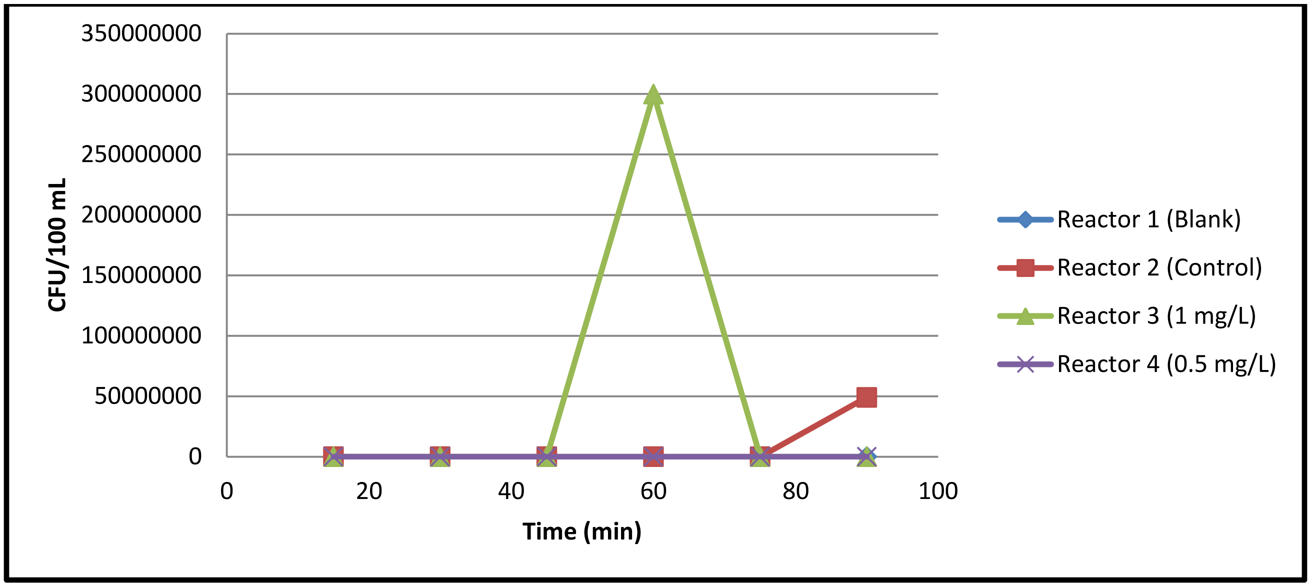



**Figure 59: CFU variation for *E. coli* inoculation in 2nd experiment**

## A.3. Third experiment

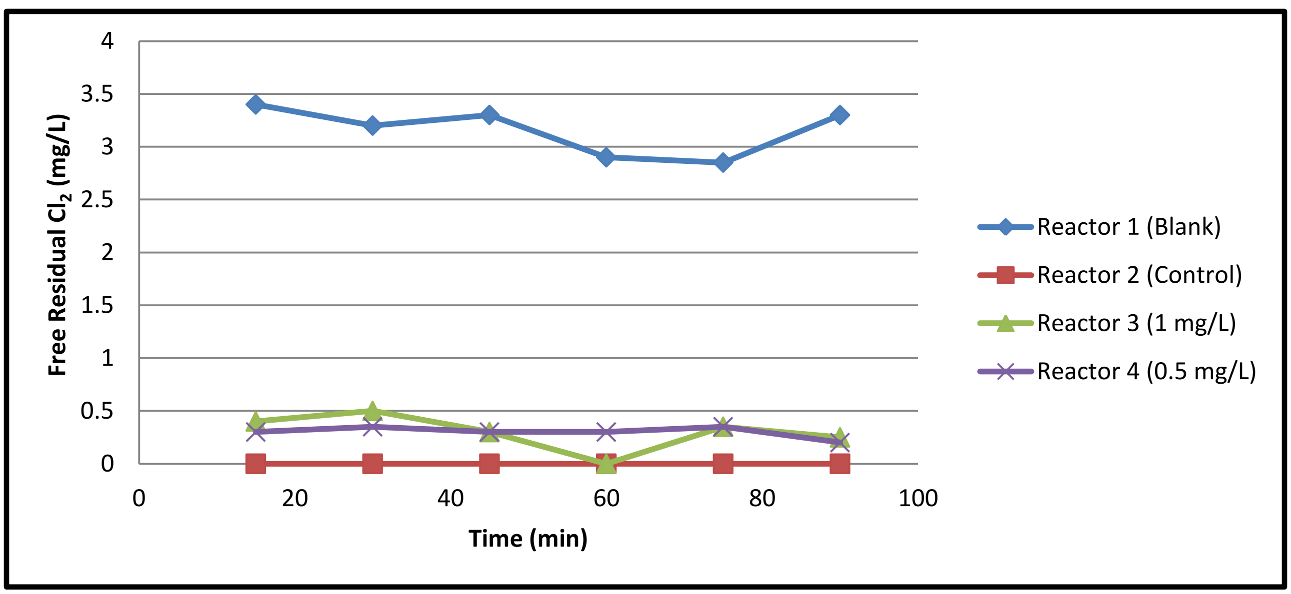



**Figure 60: Free residual chlorine concentration in 3rd experiment**

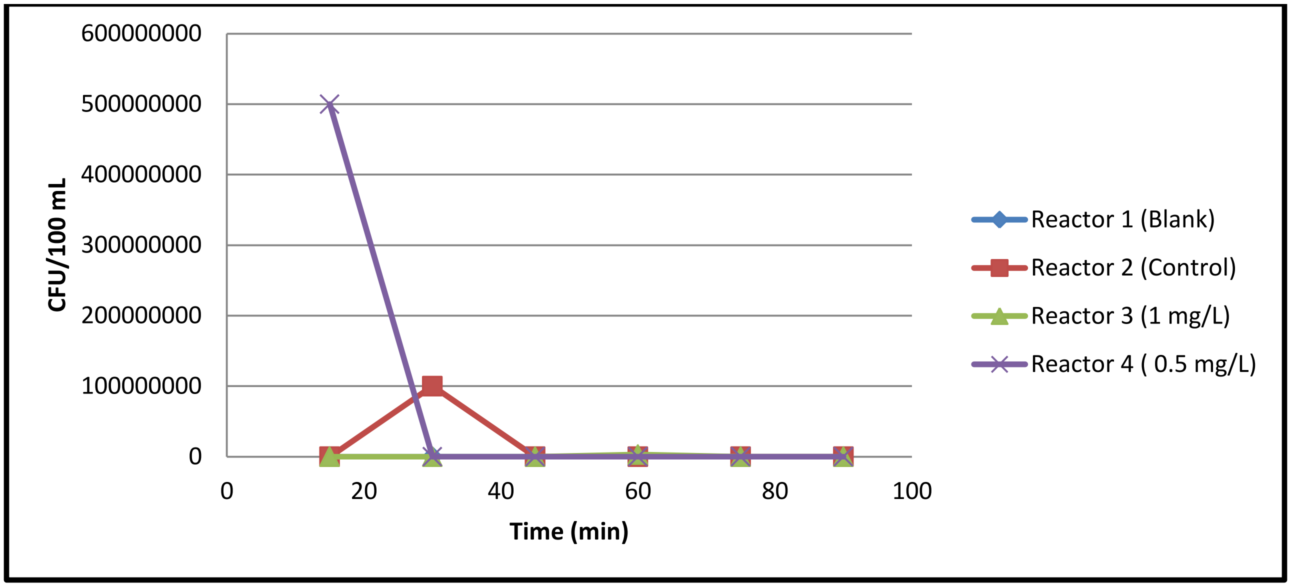



**Figure 61: CFU variation for *E. coli* inoculation in 3rd experiment**

## A.4. Fourth experiment

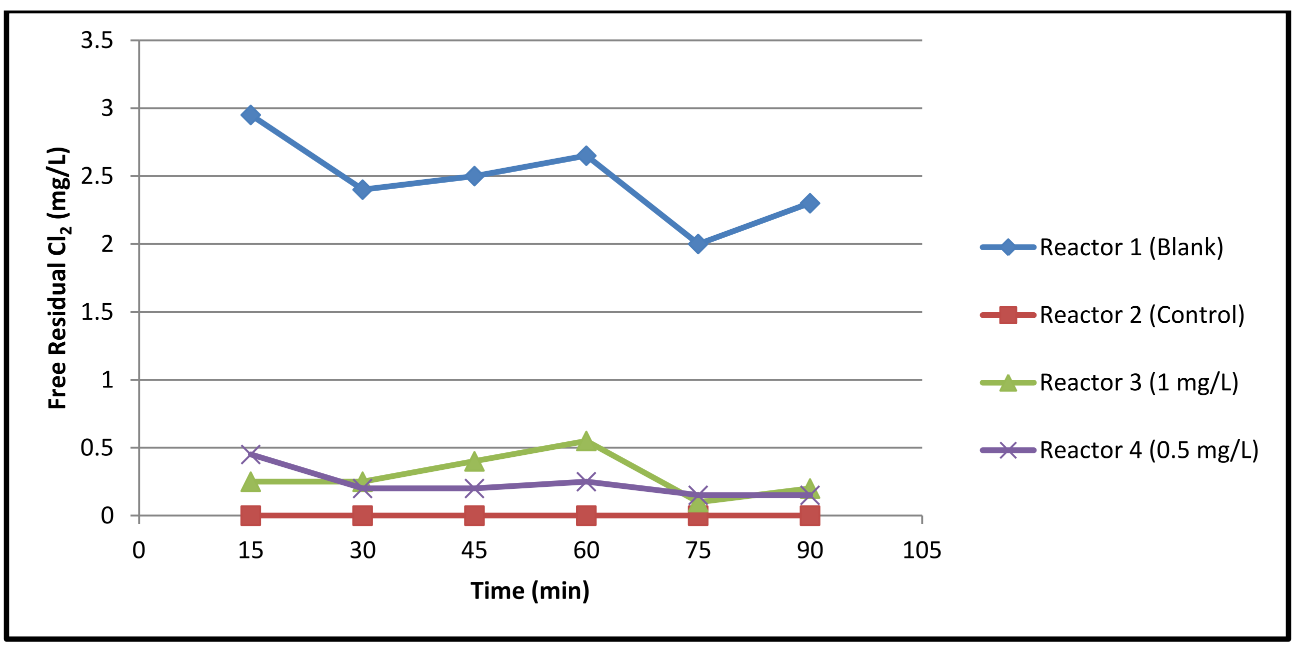



**Figure 62: Free residual chlorine concentration in 4th experiment**

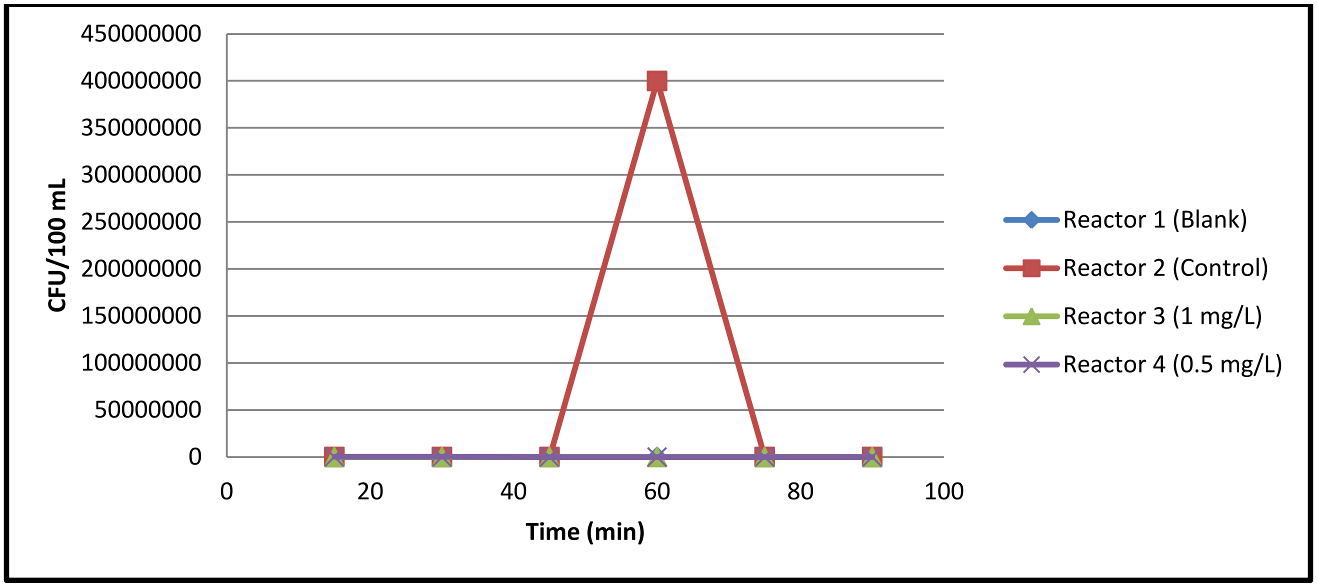



**Figure 63: CFU variation for *E. coli* inoculation in 4$^{th}$ experiment**

## A.5. Fifth experiment

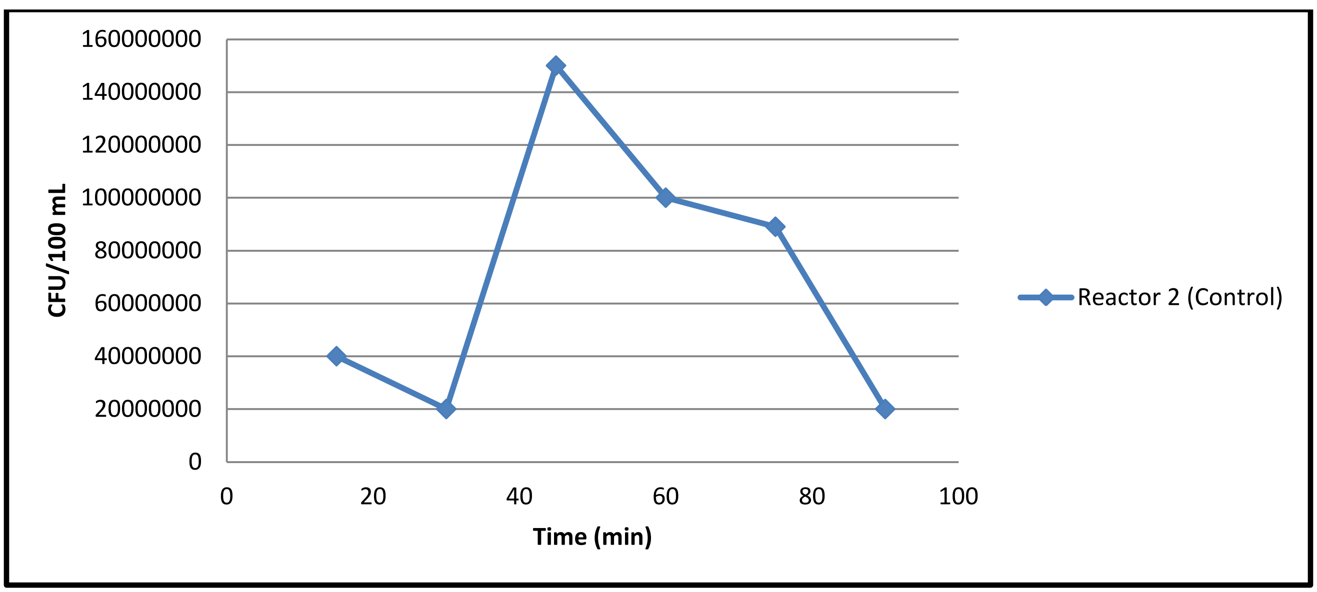



**Figure 64: CFU variation for reactor 2 *E. coli* inoculation in 5$^{th}$ experiment**

## B. Disinfection by-products

This part of the appendix pertains to all experiments with disinfection by products such as those with rainwater reactors and those with humic acid spike.

### B.1. Experiments with rainwater and *E. coli* spike

The following figures show results obtained from the two (2) experiments done to determine DBP production when spiking chlorine in rainwater reactor containing *E. coli*.

#### B.1.1. Experiment 1

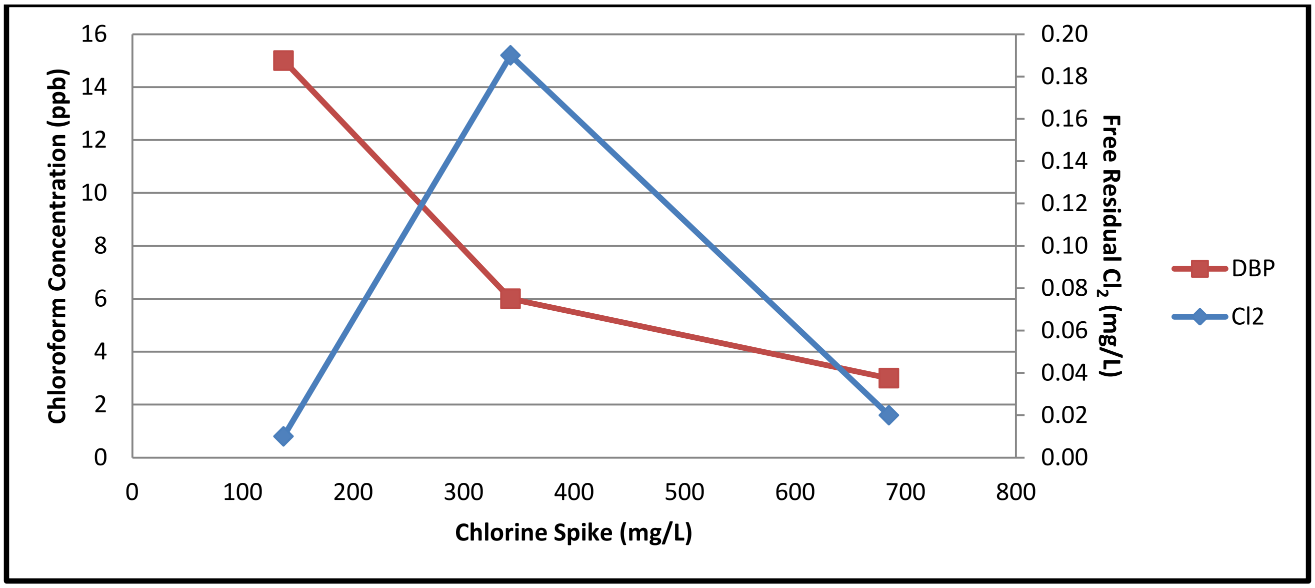



**Figure 65: Chloroform and residual chlorine plots for 1st experiment**

#### B.1.2. Experiment 2

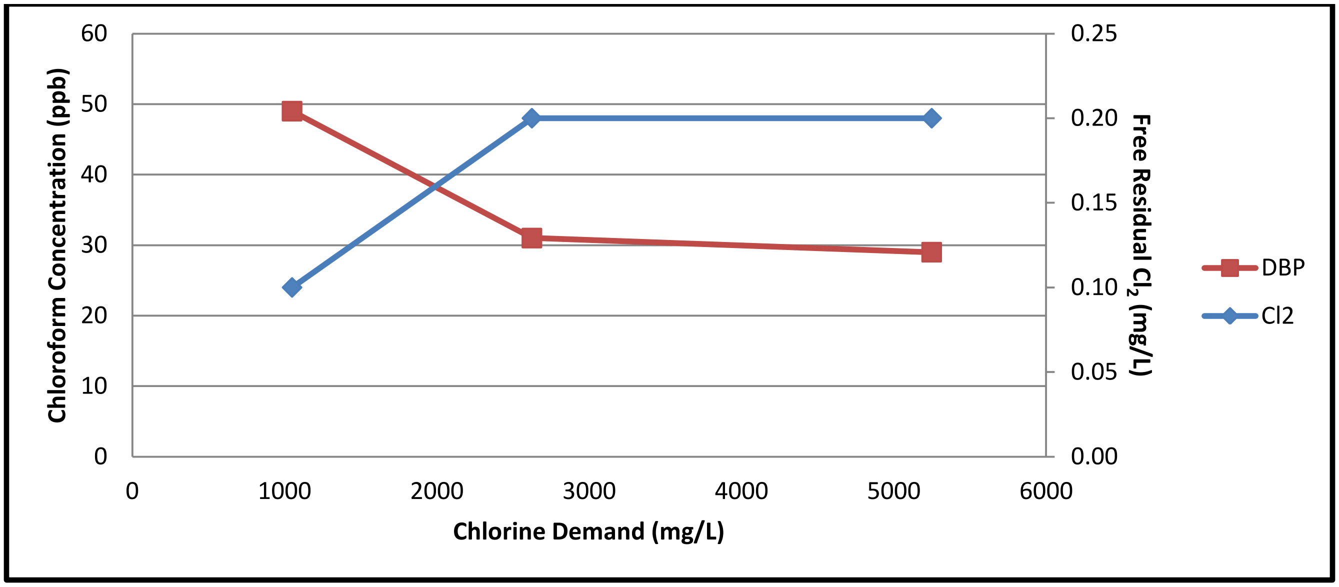



**Figure 66: Chloroform and residual chlorine plots for 2nd experiment**

## B.2. Experiments with humic acid spike

The following figures show results obtained from the two (2) experiments done to determine DBP production when spiking chlorine to reactors containing humic acid.

### B.2.1. Experiment 1

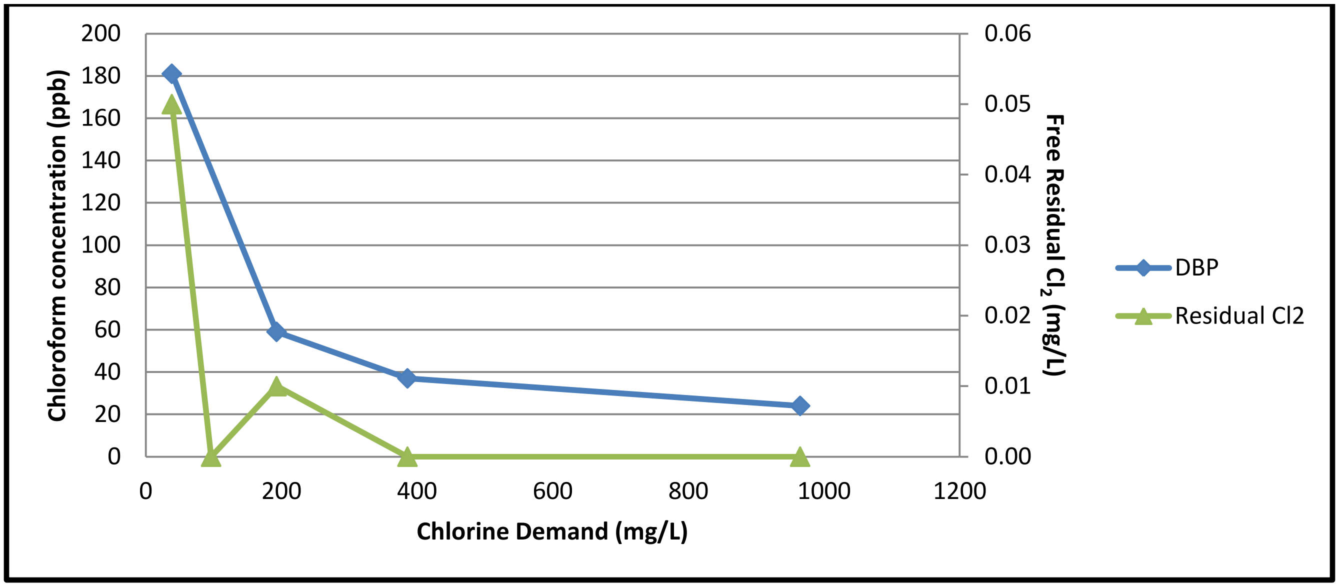
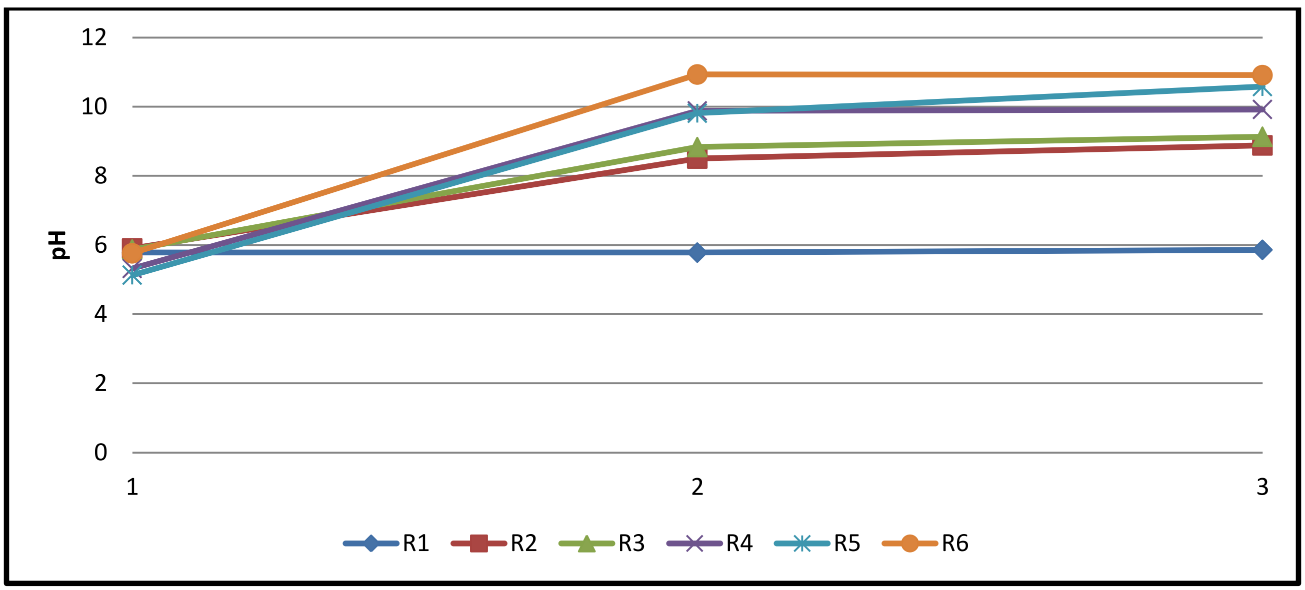



**Figure 67: Chloroform and residual chlorine plots for 1st experiment with humic acid**




Notes: Numbers 1, 2 and 3 in graph represent before adding chlorine, right after adding chlorine and after 30 minute contact time stages.

**Figure 68: pH variation in humic acid DBP 1st experiment**

### B.2.2. Experiment 2

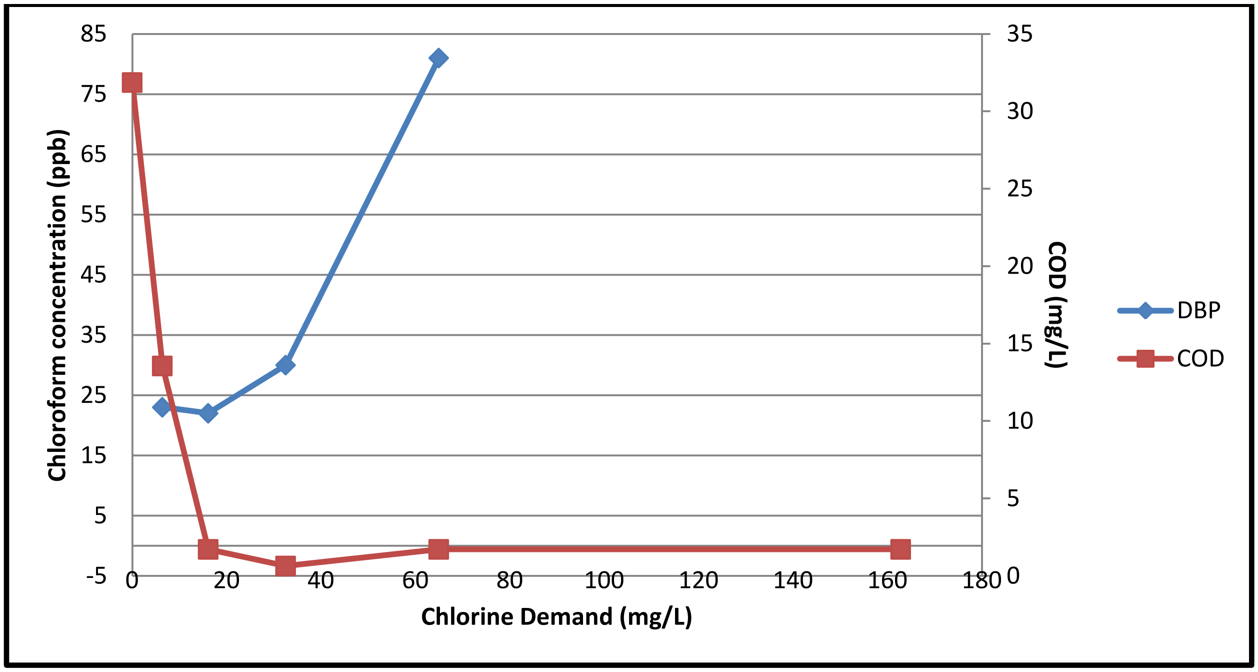
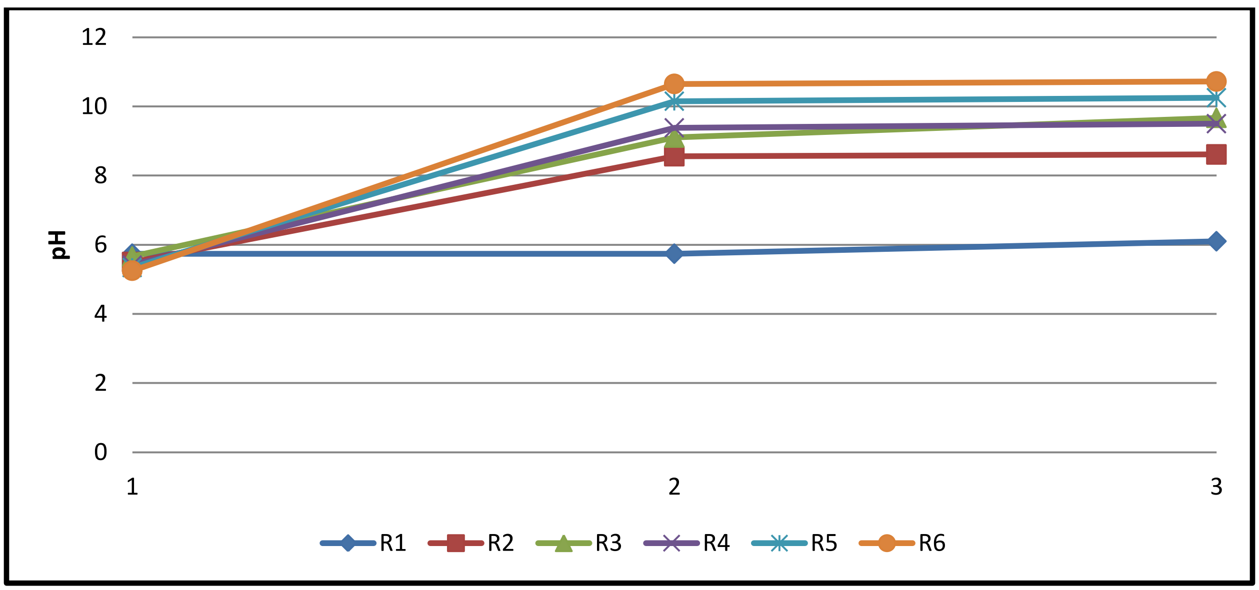



**Figure 69: Chloroform and residual chlorine plots for 2nd experiment with humic acid**




Notes: Numbers 1, 2 and 3 in graph represent before adding chlorine, right after adding chlorine and after 30 minute contact time stages.

**Figure 70: pH variation in humic acid DBP 2nd experiment**

## C. Calcium Alginate Beads

Part C of the Appendix section corresponds to all experiments done with concern to calcium alginate beads, such as kinetics, adsorption and filter column experiments.

### C.1. Adsorption Kinetics

#### C.1.1. Experiment 1

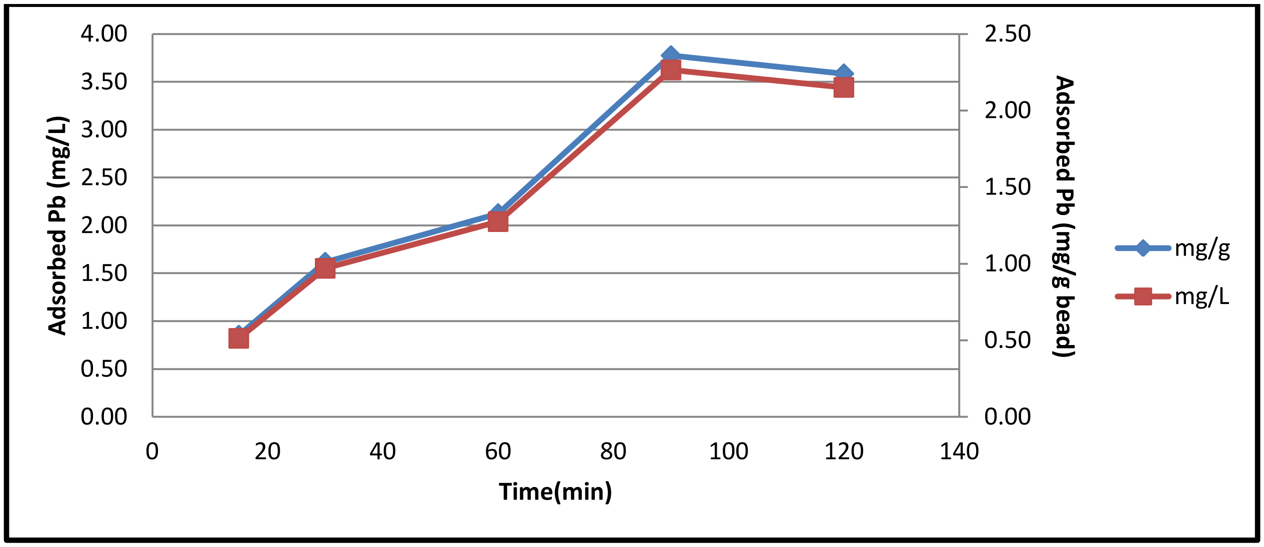



**Figure 71: AG kinetic adsorption**

#### C.1.2. Experiment 2

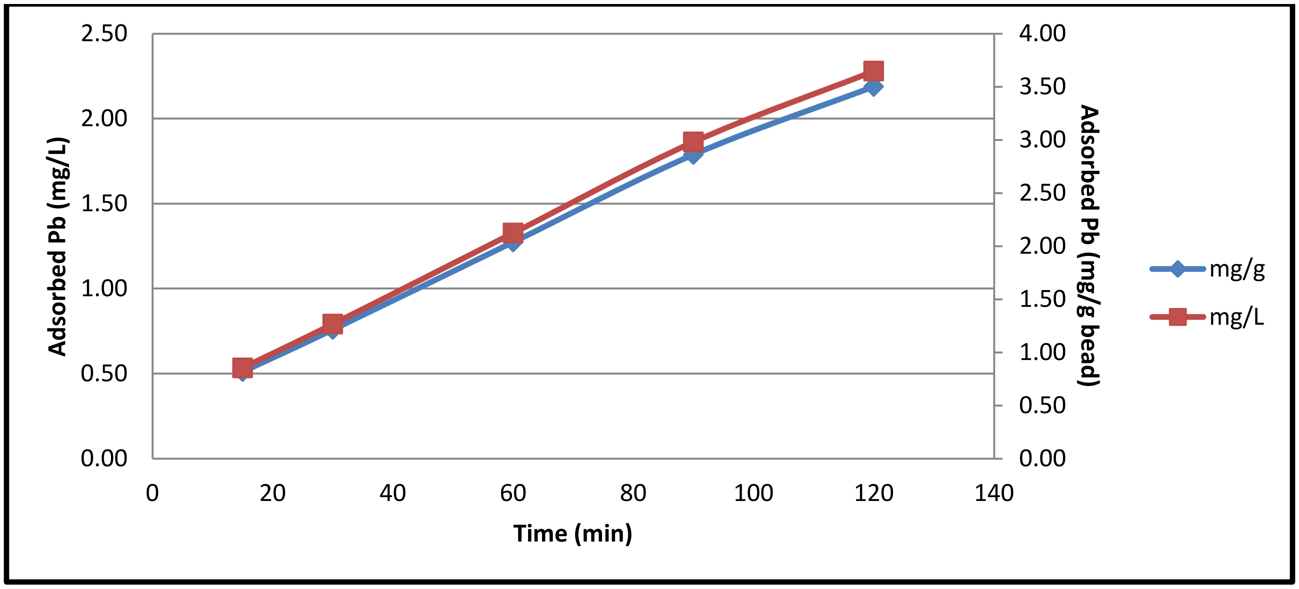



**Figure 72: AG kinetic adsorption**

## C.2. Adsorption Kinetics

### C.2.1. Adsorption experiment 1

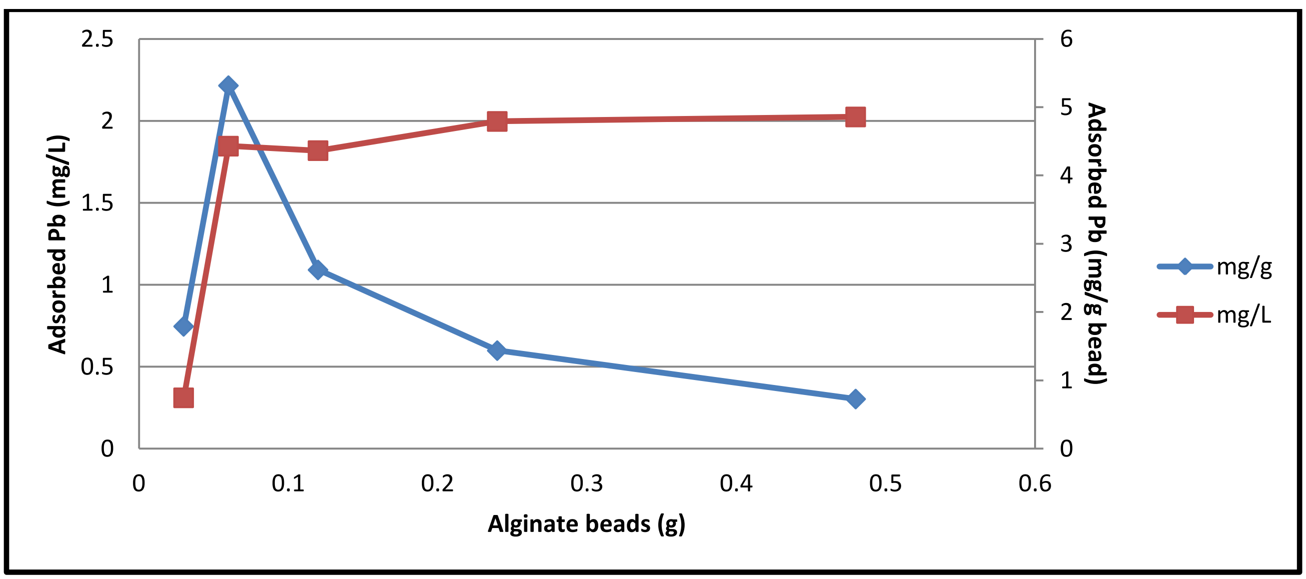



**Figure 73: AG sorption to 5 ppm lead solution for 1st experiment**

### C.2.2. Adsorption experiment 2

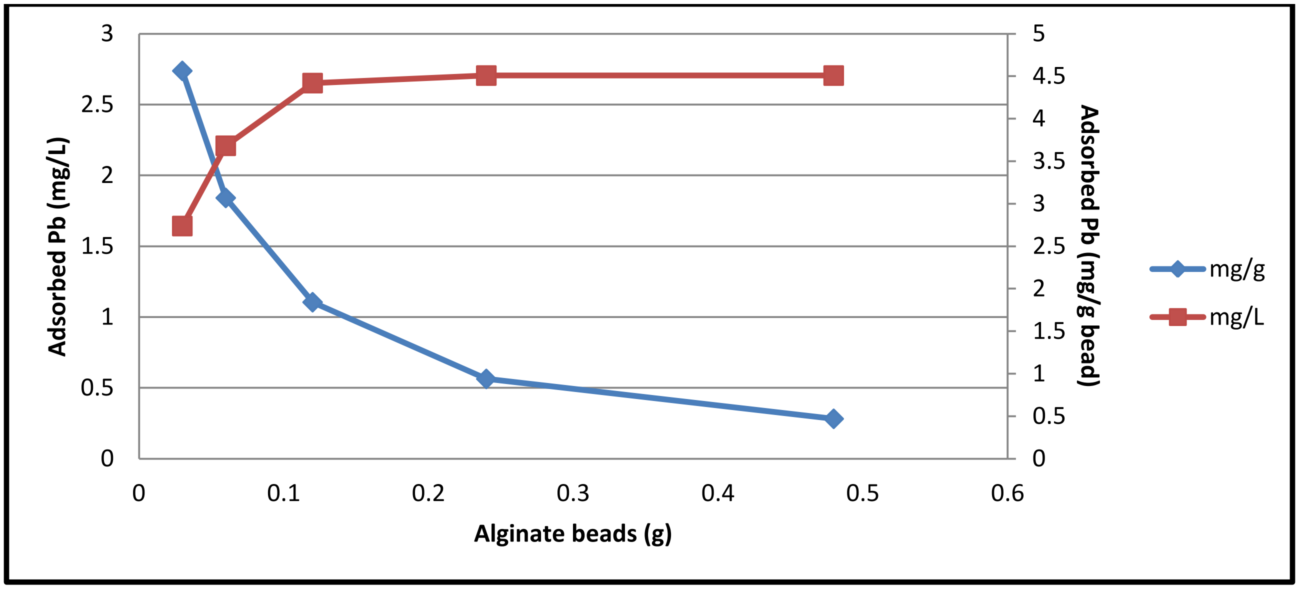



**Figure 74: AG sorption to 5 ppm lead solution for 2nd experiment**

## C.3. Filter column experiments

### C.3.1. Column experiment 1

**Table 22: Filter column results for both AG and AC for 1st experiment**

| | Initial | AC | AG |
|---|---|---|---|
| pH | 5.35 | 0.775701 | 1.02243 |
| COD (mg/L) | 11.4052541 | 0.9056 | 3.643205 |
| Conductivity (μS/cm) | 10.06 | 4.44334 | 32.40557 |
| Turbidity (NTU) | 4.58 | 0.360262 | 0.683406 |
| E-coli (CFU/100 mL) | | | |
| Lead (ppm) | UDL | 1.02924 | 1.02924 |
| Removed | - | 2.93 | 1.45 |
| Removed % | - | 63.9738 | 31.65939 |

### C.3.2. Column experiment 2

**Table 23: Filter column results for both AG and AC for 2nd experiment**

| | Initial | AC | AG |
|---|---|---|---|
| **pH** | 6.68 | 5.05 | 6.31 |
| **COD (mg/L)** | 32.96681 | 20.03578 | 45.89784 |
| **Conductivity (μS/cm)** | 50.9 | 35.2 | 73.1 |
| **Turbidity (NTU)** | 10.9 | 1.77 | 3.83 |
| **E-coli (CFU/100 mL)** | 70000 | 300000 | 1000000 |
| **Lead (ppm)** | UDL | UDL | UDL |
| **Turbidity Removed** | - | 9.13 | 7.07 |
| **Turbidity Removed %** | - | 83.76147 | 64.86239 |
| **E-coli Removed** | - | -230000 | -930000 |
| **E-coli Removed %** | - | -328.571 | -1328.57 |

## D. POE-CPU experiments

This part of the Appendix shows results from all POE-CPU runs, including those with the addition of AC and AG.

### D.1. POE-CPU run

Figures in this section show all water quality parameters measured in all three (3) experiments done with the system with its original design

#### D.1.1. Experiment 1

**Table 24: Water quality parameters for POE-CPU run 1st experiment**

| Time: 30 minutes | | | | |
|---|---|---|---|---|
| **Parameter** | **Rain** | **Gravel** | **Sand** | **Disinfection** |
| **pH** | 6.58 | 6.74 | 6.75 | 6.34 |
| **Conductivity (µS/cm)** | | | | |
| **E-coli (CFU/100mL)** | 1.2E+08 | 38000000 | >10^4 | >10^0 |
| **COD (mg/L)** | 34.01507 | 43.705 | 42.62834 | 20.01852 |
| **Turbidity (NTU)** | 1.61 | 1.55 | 0.87 | 0.99 |
| **Free $Cl_2$ (mg/L)** | | | | 0.566667 |
| **Consumed($Cl_2$)** | | | | 0.8474747 |
| **Time: 60 minutes** | | | | |
| **Parameter** | **Re** | **Gravel** | **Sand** | **Disinfection** |
| **pH** | 7.05 | 6.88 | 6.57 | 6.45 |
| **Conductivity (µS/cm)** | | | | |
| **E-coli (CFU/100mL)** | 1.2E+08 | 61000000 | >10^4 | >10^0 |
| **COD (mg/L)** | 34.01507 | 30.7851 | 26.47847 | 31.86176 |
| **Turbidity (NTU)** | 1.6 | 0.99 | 0.81 | 0.82 |
| **Free $Cl_2$ (mg/L)** | | | | 0.033333 |
| **Consumed($Cl_2$)** | | | | 1.3808081 |

### D.1.2. Experiment 2

**Table 25: Water quality parameters for POE-CPU run 2nd experiment**

| Time: 30 minutes | | | | |
|---|---|---|---|---|
| **Parameter** | **Re** | **Gravel** | **Sand** | **Disinfection** |
| **pH** | 6.26 | 6.58 | 6.84 | 6.79 |
| **Conductivity (µS/cm)** | 365 | 362 | 334 | 367 |
| **E-coli (CFU/100mL)** | | | | |
| **COD (mg/L)** | 38.32171 | 25.40181 | 51.2416 | 48.01163 |
| **Turbidity (NTU)** | 3.6 | 3.4 | 1.5 | 1.6 |
| **Free $Cl_2$ (mg/L)** | | | | 1.35 |
| **DBP (ppb)** | | | | 97 |
| **Consumed($Cl_2$)** | | | | 5.35 |
| **Time: 60 minutes** | | | | |
| **Parameter** | **Re** | **Gravel** | **Sand** | **Disinfection** |
| **pH** | 6.56 | 6.83 | 6.57 | 6.45 |
| **Conductivity (µS/cm)** | 347 | 355 | 357 | 385 |
| **E-coli (CFU/100mL)** | | | | |
| **COD (mg/L)** | 38.32171 | 42.62834 | 51.2416 | 38.32171 |
| **Turbidity (NTU)** | 3.8 | 3.2 | 1.5 | 1.8 |
| **Free $Cl_2$ (mg/L)** | | | | 0.7 |
| **DBP (ppb)** | | | | 5 |
| **Consumed($Cl_2$)** | | | | 5.9993 |

### D.1.3. Experiment 3

**Table 26: Water quality parameters for POE-CPU run 3rd experiment**

| Time: 30 minutes | | | | |
|---|---|---|---|---|
| **Parameter** | **Re** | **Gravel** | **Sand** | **Disinfection** |
| **pH** | 6.35 | 6.27 | 5.69 | 7.39 |
| **Conductivity (µS/cm)** | 166.6 | 166.7 | 150.6 | 331 |
| **E-coli (CFU/100mL)** | | | | |
| **COD (mg/L)** | 4.945306 | 0.638674 | -2.5913 | -9.05125 |
| **Turbidity (NTU)** | 9.64 | 9.99 | 7.54 | 6.9 |
| **Free $Cl_2$ (mg/L)** | | | | 58 |
| **DBP (ppb)** | | | | 42 |
| **Consumed($Cl_2$)** | | | | 82 |
| **Time: 60 minutes** | | | | |
| **Parameter** | **Re** | **Gravel** | **Sand** | **Disinfection** |
| **pH** | 6.56 | 6.83 | 6.57 | 6.45 |
| **Conductivity (µS/cm)** | 25 | 25 | 25 | 25 |
| **E-coli (CFU/100mL)** | 166.7 | 167.7 | 167.1 | 332 |
| **COD (mg/L)** | | | | |
| **Turbidity (NTU)** | 0.638674 | 1.715332 | -2.5913 | -9.05125 |
| **Free $Cl_2$ (mg/L)** | 17.6 | 11.3 | 7.75 | 7.45 |
| **DBP (ppb)** | | | | 0.7 |
| **Consumed($Cl_2$)** | | | | 139.3 |

### D.1.4. Comparison between all experiments with the POE-CPU

The results shown in the next table shows the normalized results (C/C0) of all three (3) POE-CPU experiments. These values are used for bar charts presented in the results and discussion. Additional statistical calculations were made and are also presented in the table.

**Table 27: Normalized results for experiments with POE-CPU**

| pH | | | | |
|---|---|---|---|---|
| | Gravel 30 | Gravel 60 | Sand 30 | Sand 60 |
| Experiment 1 | 1.024 | 0.976 | 1.026 | 0.932 |
| Experiment 2 | 1.051 | 1.041 | 1.093 | 1.002 |
| Experiment 3 | 0.987 | 1.041 | 0.896 | 1.002 |
| Average | 1.021 | 1.019 | 1.005 | 0.978 |
| Std dev | 0.032 | 0.038 | 0.100 | 0.040 |
| Variance coefficient | 0.031 | 0.037 | 0.099 | 0.041 |
| Variance | 0.001 | 0.001 | 0.010 | 0.002 |
| Conductivity (µS/cm / µS/cm) | | | | |
| | Gravel 30 | Gravel 60 | Sand 30 | Sand 60 |
| Experiment 1 | - | - | - | - |
| Experiment 2 | 0.992 | 1.023 | 0.915 | 1.029 |
| Experiment 3 | 1.001 | 1.006 | 0.904 | 1.002 |
| Average | 0.996 | 1.015 | 0.910 | 1.016 |
| Std dev | 0.006 | 0.012 | 0.008 | 0.019 |
| Variance coefficient | 0.006 | 0.012 | 0.009 | 0.018 |
| Variance | 0.000 | 0.000 | 0.000 | 0.000 |
| COD (mg/L / mg/L) | | | | |
| | Gravel 30 | Gravel 60 | Sand 30 | Sand 60 |
| Experiment 1 | 1.321 | 0.893 | 1.286 | 0.750 |
| Experiment 2 | 0.663 | 1.112 | 1.337 | 1.337 |
| Experiment 3 | 0.129 | 2.686 | - | - |
| Average | 0.704 | 1.564 | 1.311 | 1.044 |
| Std dev | 0.597 | 0.978 | 0.036 | 0.415 |
| Variance coefficient | 0.848 | 0.625 | 0.028 | 0.398 |
| Variance | 0.357 | 0.956 | 0.001 | 0.172 |
| Turbidity (NTU/NTU) | | | | |
| | Gravel 30 | Gravel 60 | Sand 30 | Sand 60 |
| Experiment 1 | 0.963 | 0.619 | 0.540 | 0.506 |
| Experiment 2 | 0.944 | 0.842 | 0.417 | 0.395 |
| Experiment 3 | 1.036 | 0.642 | 0.782 | 0.440 |
| Average | 0.981 | 0.701 | 0.580 | 0.447 |
| Std dev | 0.049 | 0.123 | 0.186 | 0.056 |
| Variance coefficient | 0.050 | 0.175 | 0.321 | 0.125 |
| Variance | 0.002 | 0.015 | 0.035 | 0.003 |

## D.2. POE-CPU run with AC

Results shown in the following subsections correspond to water quality measurements of all experiments done with the addition of AC to the sand filter.

### D.2.1. Experiment 1

**Table 28: Water quality parameters for POE-CPU run with AC 1st experiment**

| Time: 30 minutes | | | | |
|---|---|---|---|---|
| **Parameter** | **Re** | **Gravel** | **Sand** | **Disinfection** |
| **pH** | 6.57 | 6.81 | 6.76 | 7.58 |
| **Conductivity (µS/cm)** | 318 | 301 | 86.2 | 125.8 |
| **E-coli (CFU/100mL)** | 1000000 | <10^6 | >10^6 | 0 |
| **COD (mg/L)** | 6.021963824 | 6.021964 | 4.945306 | 0.638674 |
| **Turbidity (NTU)** | 7.07 | 5.73 | 2.68 | 2.58 |
| **Free $Cl_2$ (mg/L)** | | | | 23.2 |
| **DBP (ppb)** | | | | -9 |
| **Consumed($Cl_2$)** | | | | 3.55 |
| **Time: 60 minutes** | | | | |
| **Parameter** | **Re** | **Gravel** | **Sand** | **Disinfection** |
| **pH** | 7.27 | 7.19 | 6.56 | 7.21 |
| **Conductivity (µS/cm)** | 321 | 311 | 231 | 193.6 |
| **E-coli (CFU/100mL)** | <10^6 | <10^6 | 21000000 | 0 |
| **COD (mg/L)** | 7.098621878 | 7.098622 | 3.868648 | 0.638674 |
| **Turbidity (NTU)** | 7.6 | 6.05 | 4.01 | 4.16 |
| **Free $Cl_2$ (mg/L)** | | | | 21.7 |
| **DBP (ppb)** | | | | -8 |
| **Consumed($Cl_2$)** | | | | 5.05 |

### D.2.2. Experiment 2

**Table 29: Water quality parameters for POE-CPU run with AC 2nd experiment**

| Time: 30 minutes | | | | |
|---|---|---|---|---|
| **Parameter** | **Re** | **Gravel** | **Sand** | **Disinfection** |
| **pH** | 5.3 | 7.21 | 6.21 | 6.7 |
| **Conductivity (µS/cm)** | 34.7 | 56.3 | 139.6 | 136 |
| **E-coli (CFU/100mL)** | 43000000 | 32000000 | | 0 |
| **COD (mg/L)** | 43.705 | 38.32171 | 18.94186 | 18.94186 |
| **Turbidity (NTU)** | 6.11 | 5.1 | 2.72 | 2.94 |
| **Free $Cl_2$ (mg/L)** | | | | 8.1 |
| **DBP (ppb)** | | | | -46 |
| **Consumed($Cl_2$)** | | | | |
| **Time: 60 minutes** | | | | |
| **Parameter** | **Re** | **Gravel** | **Sand** | **Disinfection** |
| **pH** | 5.35 | 6.97 | 5.95 | 7.09 |
| **Conductivity (µS/cm)** | 33.7 | 44.4 | 62.2 | 51.7 |
| **E-coli (CFU/100mL)** | 54000000 | 46000000 | | 0 |
| **COD (mg/L)** | 43.705 | 40.47502 | 30.7851 | 25.40181 |
| **Turbidity (NTU)** | 6.07 | 5.59 | 4.65 | 4.86 |
| **Free $Cl_2$ (mg/L)** | | | | 5.9 |
| **DBP (ppb)** | | | | -38 |
| **Consumed($Cl_2$)** | | | | |

### D.2.3. Experiment 3

**Table 30: Water quality parameters for POE-CPU run with AC 3rd experiment**

| Time: 30 minutes | | | | |
|---|---|---|---|---|
| Parameter | Re | Gravel | Sand | Disinfection |
| pH | 6.97 | 8.34 | 7.41 | 7.52 |
| Conductivity (µS/cm) | 49.2 | 54.9 | 43.5 | 61.9 |
| E-coli (CFU/100mL) | | | 97000000 | 3 |
| COD (mg/L) | 51.2416 | 48.01163 | 27.55512 | 24.32515 |
| Turbidity (NTU) | 6.2 | 5.51 | 3.28 | 3.09 |
| Free $Cl_2$ (mg/L) | | | | 2.9 |
| DBP (ppb) | | | | -5 |
| Consumed($Cl_2$) | | | | -2.9 |
| **Time: 60 minutes** | | | | |
| Parameter | Re | Gravel | Sand | Disinfection |
| pH | 6.82 | 7.88 | 7.31 | 7.37 |
| Conductivity (µS/cm) | 49 | 54.3 | 48.4 | 66.8 |
| E-coli (CFU/100mL) | | | | |
| COD (mg/L) | 53.39492 | 42.62834 | 28.63178 | 35.09173 |
| Turbidity (NTU) | 6.3 | 5.44 | 4.66 | 5.27 |
| Free $Cl_2$ (mg/L) | | | | 0.8 |
| DBP (ppb) | | | | 8 |
| Consumed($Cl_2$) | | | | -0.8 |

### D.2.4. Comparison between all experiments of the POE-CPU with AC

The results shown in the following table shows the normalized results (C/C0) of all three (3) POE-CPU experiments with the addition of AC. Bar charts presented in the results and discussion belong to these values. Additional statistical calculations were made and are also presented.

**Table 31: Normalized results for experiments with POE-CPU with AC**

| pH | | | | |
|---|---|---|---|---|
| | Gravel 30 | Gravel 60 | Sand 30 | Sand 60 |
| Experiment 1 | 1.037 | 0.989 | 1.029 | 0.902 |
| Experiment 2 | 1.097 | 0.959 | 0.945 | 0.818 |
| Experiment 3 | 1.269 | 1.084 | 1.128 | 1.006 |
| Average | 1.134 | 1.011 | 1.034 | 0.909 |
| Std dev | 0.121 | 0.065 | 0.091 | 0.094 |
| Variance coefficient | 0.106 | 0.065 | 0.088 | 0.103 |
| Variance | 0.015 | 0.004 | 0.008 | 0.009 |
| Conductivity (µS/cm / µS/cm) | | | | |
| | Gravel 30 | Gravel 60 | Sand 30 | Sand 60 |
| Experiment 1 | 0.947 | 0.969 | 0.271 | 0.720 |
| Experiment 2 | 0.177 | 0.138 | 0.439 | 0.194 |
| Experiment 3 | 0.173 | 0.169 | 0.137 | 0.151 |
| Average | 0.432 | 0.425 | 0.282 | 0.355 |
| Std dev | 0.446 | 0.471 | 0.151 | 0.317 |
| Variance coefficient | 1.031 | 1.107 | 0.536 | 0.893 |
| Variance | 0.199 | 0.222 | 0.023 | 0.100 |
| COD (mg/L / mg/L) | | | | |
| | Gravel 30 | Gravel 60 | Sand 30 | Sand 60 |
| Experiment 1 | 1.000 | 1.000 | 0.821 | 0.545 |
| Experiment 2 | 6.364 | 5.702 | 3.145 | 4.337 |
| Experiment 3 | 7.973 | 6.005 | 4.576 | 4.033 |
| Average | 5.112 | 4.236 | 2.847 | 2.972 |
| Std dev | 3.651 | 2.806 | 1.895 | 2.107 |
| Variance coefficient | 0.714 | 0.663 | 0.665 | 0.709 |
| Variance | 13.330 | 7.875 | 3.591 | 4.440 |
| Turbidity (NTU/NTU) | | | | |
| | Gravel 30 | Gravel 60 | Sand 30 | Sand 60 |
| Experiment 1 | 0.810 | 0.796 | 0.379 | 0.528 |
| Experiment 2 | 0.721 | 0.736 | 0.385 | 0.612 |
| Experiment 3 | 0.779 | 0.716 | 0.464 | 0.613 |
| Average | 0.770 | 0.749 | 0.409 | 0.584 |
| Std dev | 0.045 | 0.042 | 0.047 | 0.049 |
| Variance coeffcient | 0.059 | 0.056 | 0.116 | 0.084 |
| Variance | 0.002 | 0.002 | 0.002 | 0.002 |

## D.3. POE-CPU run with AG

The tables presented in the following subsections show water quality parameters of all experiments done with the addition of AG beads to the sand filter.

### D.3.1. Experiment 1

**Table 32: Water quality parameters for POE-CPU run with AG 1st experiment**

| Time: 30 minutes | | | | |
|---|---|---|---|---|
| **Parameter** | **Re** | **Gravel** | **Sand** | **Disinfection** |
| **pH** | 6.453 | 6.81 | 6.921 | |
| **Conductivity (µS/cm)** | 28.1 | 41.6 | 33.1 | |
| **E-coli (CFU/100mL)** | - | 4000000 | 24000000 | 2 |
| **COD (mg/L)** | 42.62834 | 36.16839 | 23.24849 | 34.01507 |
| **Turbidity (NTU)** | 10.6 | 6.6 | 3.2 | |
| **Free $Cl_2$ (mg/L)** | | | | 12.5 |
| **DBP (ppb)** | | | | |
| **Consumed($Cl_2$)** | | | | |
| **Time: 60 minutes** | | | | |
| **Parameter** | **Re** | **Gravel** | **Sand** | **Disinfection** |
| **pH** | 6.385 | 6.852 | 6.909 | |
| **Conductivity (µS/cm)** | 30.5 | 42 | 40.5 | TMTC |
| **E-coli (CFU/100mL)** | 1E+08 | - | 77000000 | 34.01507 |
| **COD (mg/L)** | 42.62834 | 41.55168 | 30.7851 | |
| **Turbidity (NTU)** | 11.4 | 7.5 | 4.5 | |
| **Free $Cl_2$ (mg/L)** | | | | 13 |
| **DBP (ppb)** | | | | |
| **Consumed($Cl_2$)** | | | | |

Notes: Some parameters for the disinfection process weren't able to be measured because of lack of sample

### D.3.2. Experiment 2

**Table 33: Water quality parameters for POE-CPU run with AG 2nd experiment**

| Time: 30 minutes | | | | |
|---|---|---|---|---|
| **Parameter** | **Re** | **Gravel** | **Sand** | **Disinfection** |
| **pH** | 6.482 | 7.754 | 7.474 | 7.712 |
| **Conductivity (µS/cm)** | 38.7 | 53.1 | 120.3 | 148.9 |
| **E-coli (CFU/100mL)** | | | 2E+08 | |
| **COD (mg/L)** | 45.85831 | 41.55168 | 4.945306 | 26.47847 |
| **Turbidity (NTU)** | 10.6 | 7.8 | 3.3 | 4.6 |
| **Free $Cl_2$ (mg/L)** | | | | 5.4 |
| **DBP (ppb)** | | | UR | -32 |
| **Consumed($Cl_2$)** | | | | |
| **Time: 60 minutes** | | | | |
| **Parameter** | **Re** | **Gravel** | **Sand** | **Disinfection** |
| **pH** | 6.671 | 7.127 | 7.148 | 7.461 |
| **Conductivity (µS/cm)** | 36.8 | 44.2 | 57.6 | 52.4 |
| **E-coli (CFU/100mL)** | 2E+09 | 5.7E+09 | 1.3E+09 | |
| **COD (mg/L)** | 46.93497 | 43.705 | 35.09173 | 35.09173 |
| **Turbidity (NTU)** | 10.7 | 8.3 | 6.1 | 6.7 |
| **Free $Cl_2$ (mg/L)** | | | | 8.3 |
| **DBP (ppb)** | | | | -36 |
| **Consumed($Cl_2$)** | | | | |

### D.3.3. Experiment 3

**Table 34: Water quality parameters for POE-CPU run with AG 3rd experiment**

| Time: 30 minutes | | | | |
|---|---|---|---|---|
| **Parameter** | **Re** | **Gravel** | **Sand** | **Disinfection** |
| **pH** | 7.405 | 7.533 | 7.415 | 7.596 |
| **Conductivity (µS/cm)** | 40.5 | 47 | 37.4 | 38.9 |
| **E-coli (CFU/100mL)** | 74000000 | 89500000 | 2000000 | 0 |
| **COD (mg/L)** | 48.01163 | 43.705 | 26.47847 | 26.47847 |
| **Turbidity (NTU)** | 7.72 | 6.66 | 3.47 | 4.02 |
| **Free $Cl_2$ (mg/L)** | | | | 12.5 |
| **DBP (ppb)** | | | | -2 |
| **Consumed($Cl_2$)** | | | | 0.9 |
| **Time: 60 minutes** | | | | |
| **Parameter** | **Re** | **Gravel** | **Sand** | **Disinfection** |
| **pH** | 7.119 | 7.359 | 7.337 | 7.543 |
| **Conductivity (µS/cm)** | 40.8 | 47.4 | 45.5 | 39 |
| **E-coli (CFU/100mL)** | 59000000 | 1.21E+08 | 4000000 | 0 |
| **COD (mg/L)** | 46.93497 | 44.78165 | 40.47502 | 41.55168 |
| **Turbidity (NTU)** | 8.06 | 7.13 | 5.77 | 6.52 |
| **Free $Cl_2$ (mg/L)** | | | | 7 |
| **DBP (ppb)** | | | | -18 |
| **Consumed($Cl_2$)** | | | | 6.4 |

### D.3.4. Comparison between all experiments with the POE-CPU

The following table presents the normalized results (C/C0) for 30 minutes and 60 minutes samples of all three (3) POE-CPU experiments done with the addition of AG. Bar charts presented in the results and discussion section belong to these values. Statistical calculations, such as standard deviation and variance are also presented.

Table 35: Normalized results for experiments with POE-CPU with AG

| pH | | | | |
|---|---|---|---|---|
| | Gravel 30 | Gravel 60 | Sand 30 | Sand 60 |
| Experiment 1 | 1.055 | 1.073 | 1.073 | 1.082 |
| Experiment 2 | 1.196 | 1.068 | 1.153 | 1.072 |
| Experiment 3 | 1.017 | 1.034 | 1.001 | 1.031 |
| Average | 1.090 | 1.058 | 1.076 | 1.061 |
| Std dev | 0.094 | 0.022 | 0.076 | 0.027 |
| Variance coefficient | 0.087 | 0.020 | 0.071 | 0.026 |
| Variance | 0.009 | 0.000 | 0.006 | 0.001 |
| Conductivity (µS/cm / µS/cm) | | | | |
| | Gravel 30 | Gravel 60 | Sand 30 | Sand 60 |
| Experiment 1 | 1.480 | 1.377 | 1.178 | 1.328 |
| Experiment 2 | 1.372 | 1.201 | 3.109 | 1.565 |
| Experiment 3 | 1.160 | 1.162 | 0.923 | 1.115 |
| Average | 1.338 | 1.247 | 1.737 | 1.336 |
| Std dev | 0.163 | 0.115 | 1.195 | 0.225 |
| Variance coefficient | 0.122 | 0.092 | 0.688 | 0.168 |
| Variance | 0.026 | 0.013 | 1.428 | 0.051 |
| COD (mg/L / mg/L) | | | | |
| | Gravel 30 | Gravel 60 | Sand 30 | Sand 60 |
| Experiment 1 | 0.848 | 0.975 | 0.545 | 0.722 |
| Experiment 2 | 0.906 | 0.931 | 0.108 | 0.748 |
| Experiment 3 | 0.910 | 0.954 | 0.552 | 0.862 |
| Average | 0.888 | 0.953 | 0.402 | 0.777 |
| Std dev | 0.035 | 0.022 | 0.254 | 0.075 |
| Variance coefficient | 0.039 | 0.023 | 0.634 | 0.096 |
| Variance | 0.001 | 0.000 | 0.065 | 0.006 |
| Turbidity (NTU/NTU) | | | | |
| | Gravel 30 | Gravel 60 | Sand 30 | Sand 60 |
| Experiment 1 | 0.623 | 0.658 | 0.302 | 0.395 |
| Experiment 2 | 0.736 | 0.776 | 0.311 | 0.570 |
| Experiment 3 | 0.863 | 0.885 | 0.449 | 0.716 |
| Average | 0.740 | 0.773 | 0.354 | 0.560 |
| Std dev | 0.120 | 0.113 | 0.083 | 0.161 |
| Variance coefficient | 0.162 | 0.147 | 0.233 | 0.287 |
| Variance | 0.014 | 0.013 | 0.007 | 0.026 |

## D.4. POE-CPU treatment comparison

This final table shows the normalized results (C/C0) for all nine (9) POE-CPU experiments with the various treatments. Bar charts in the treatment comparison section belong to these values. Statistical calculations, such as standard deviation and variance are also presented.

**Table 36: Normalized results for all POE-CPU treatments**

| pH | | | | | | |
|---|---|---|---|---|---|---|
| | POE-CPU | | POE-CPU with AC | | POE-CPU with AG | |
| | Gravel | Sand | Gravel | Sand | Gravel | Sand |
| Experiment 1 (30 minutes) | 1.024 | 1.026 | 1.037 | 1.029 | 1.055 | 1.073 |
| Experiment 2 (30 minutes) | 1.051 | 1.093 | 1.097 | 0.945 | 1.196 | 1.153 |
| Experiment 3 (30 minutes) | 0.987 | 0.896 | 1.269 | 1.128 | 1.017 | 1.001 |
| Experiment 1 (60 minutes) | 0.976 | 0.932 | 0.989 | 0.902 | 1.073 | 1.082 |
| Experiment 2 (60 minutes) | 1.041 | 1.002 | 0.959 | 0.818 | 1.068 | 1.072 |
| Experiment 3 (60 minutes) | 1.041 | 1.002 | 1.084 | 1.006 | 1.034 | 1.031 |
| Average | 1.020 | 0.992 | 1.072 | 0.971 | 1.074 | 1.069 |
| Std dev | 0.031 | 0.070 | 0.110 | 0.108 | 0.064 | 0.052 |
| Variance coefficient | 0.031 | 0.070 | 0.103 | 0.111 | 0.059 | 0.048 |
| Variance | 0.001 | 0.005 | 0.012 | 0.012 | 0.004 | 0.003 |
| Conductivity (µS/cm / µS/cm) | | | | | | |
| | POE-CPU | | POE-CPU with AC | | POE-CPU with AG | |
| | Gravel | Sand | Gravel | Sand | Gravel | Sand |
| Experiment 1 (30 minutes) | - | - | 0.947 | 0.271 | 1.480 | 1.178 |
| Experiment 2 (30 minutes) | 0.992 | 0.915 | 0.177 | 0.439 | 1.372 | 3.109 |
| Experiment 3 (30 minutes) | 1.001 | 0.904 | 0.173 | 0.137 | 1.160 | 0.923 |
| Experiment 1 (60 minutes) | | | 0.969 | 0.720 | 1.377 | 1.328 |
| Experiment 2 (60 minutes) | 1.023 | 1.029 | 0.138 | 0.194 | 1.201 | 1.565 |
| Experiment 3 (60 minutes) | 1.006 | 1.002 | 0.169 | 0.151 | 1.162 | 1.115 |
| Average | 1.005 | 0.963 | 0.429 | 0.319 | 1.292 | 1.536 |
| Std dev | 0.013 | 0.062 | 0.410 | 0.226 | 0.135 | 0.800 |
| Variance coefficient | 0.013 | 0.065 | 0.956 | 0.708 | 0.105 | 0.521 |
| Variance | 0.000 | 0.004 | 0.168 | 0.051 | 0.018 | 0.640 |
| COD (mg/L /mg/L) | | | | | | |

| | POE-CPU | | POE-CPU with AC | | POE-CPU with AG | |
|---|---|---|---|---|---|---|
| | Gravel | Sand | Gravel | Sand | Gravel | Sand |
| **Experiment 1 (30 minutes)** | 1.321 | 1.286 | 1.000 | 0.821 | 0.848 | 0.545 |
| **Experiment 2 (30 minutes)** | 0.663 | 1.337 | 6.364 | 3.145 | 0.906 | 0.108 |
| **Experiment 3 (30 minutes)** | 0.129 | | 7.973 | 4.576 | 0.910 | 0.552 |
| **Experiment 1 (60 minutes)** | 0.893 | 0.750 | 1.000 | 0.545 | 0.975 | 0.722 |
| **Experiment 2 (60 minutes)** | 1.112 | 1.337 | 5.702 | 4.337 | 0.931 | 0.748 |
| **Experiment 3 (60 minutes)** | 2.686 | | 6.005 | 4.033 | 0.954 | 0.862 |
| **Average** | 1.134 | 1.178 | 4.674 | 2.910 | 0.921 | 0.589 |
| **Std dev** | 0.864 | 0.286 | 2.952 | 1.794 | 0.044 | 0.266 |
| **Variance coefficient** | 0.762 | 0.243 | 0.632 | 0.616 | 0.048 | 0.450 |
| **Variance** | 0.747 | 0.082 | 8.712 | 3.217 | 0.002 | 0.070 |
| **Turbidity (NTU/NTU)** | | | | | | |
| | **POE-CPU** | | **POE-CPU with AC** | | **POE-CPU with AG** | |
| | Gravel | Sand | Gravel | Sand | Gravel | Sand |
| **Experiment 1 (30 minutes)** | 0.963 | 0.540 | 0.810 | 0.379 | 0.623 | 0.302 |
| **Experiment 2 (30 minutes)** | 0.944 | 0.417 | 0.721 | 0.385 | 0.736 | 0.311 |
| **Experiment 3 (30 minutes)** | 1.036 | 0.782 | 0.779 | 0.464 | 0.863 | 0.449 |
| **Experiment 1 (60 minutes)** | 0.619 | 0.506 | 0.796 | 0.528 | 0.658 | 0.395 |
| **Experiment 2 (60 minutes)** | 0.842 | 0.395 | 0.736 | 0.612 | 0.776 | 0.570 |
| **Experiment 3 (60 minutes)** | 0.642 | 0.440 | 0.716 | 0.613 | 0.885 | 0.716 |
| **Average** | 0.841 | 0.513 | 0.760 | 0.497 | 0.757 | 0.457 |
| **Std dev** | 0.175 | 0.143 | 0.041 | 0.105 | 0.106 | 0.161 |
| **Variance coefficient** | 0.208 | 0.278 | | | 0.140 | 0.351 |
| **Variance** | 0.031 | 0.020 | 0.002 | 0.011 | 0.011 | 0.026 |