BREE 495 – Engineering Design 3

Engineering Report

Filter/Detector System for Arsenic in Drinking Water

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Abstract

In some developed and most developing countries, arsenic contamination of water is a serious concern because arsenic has been proven to be dangerous to human health and the environment. Arsenic gets into water by contamination of groundwater (usually from geologic conditions) or surface and groundwater (from mining operations). Due to the lack of accessible at-home detection and filtration, it is freely in water streams used in homes. This paper studies the existing methods of arsenic detection testing and filtration based on technical, social, environmental and economic design constraints. It then suggests an alternative method of filtration using a different combination of materials from the reviewed papers and a software method that helps with interpreting the results from detection. The combined system also includes both processes for optimized results. The final design is more cost effective, has less environmental impacts and has high arsenic sensitivity and removal efficiencies. Testing is done to see the efficiency of the chosen filtration method, and detailed explanations of how the detector software and combined systems work are made in order to give a clear idea of how the system functions.

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1. Introduction

1.1 Background

It cannot go unsaid that drinking water is a valuable and vital resource. Eliminating contaminations is vital in order to maintain clean potable water. With old and new chemicals (being made every day) that can become a contamination issue it is hard to keep. Arsenic in particular is one to be wary of as it is naturally occurring and can be an issue due to anthropogenic causes. It gets into water by contamination of groundwater (usually from geologic conditions) or surface and groundwater (from mining operations). It is a carcinogenic trace metal and is toxic to both humans and animals. It can be found in groundwater and occurs mostly in the forms of arsenite, As (III) and arsenate, As(V). As (III) is usually the predominant form in many groundwaters since it is more likely to be found in oxygen free (anaerobic) conditions while As(V) is more common in aerobic waters. In general, As (V) is more readily removed than As (III) making As(III) a larger concern(Shankar et al., 2014). According to USEPA (United States Environmental Protection Agency), arsenic is classified arsenic as a Class A carcinogen. Also, according to the World Health Organization (WHO) and USEPA, the maximum allowable concentration of As in safe drinking water is 10µg/L or 10ppb (Yamamura, 1998).

The ingestion of arsenic, even at low concentration, can result in various detrimental health issues such as pulmonary disease, cardiovascular disease, nervous system dysfunction, and also cancer of the lung, kidney and skin (Hong, et al., 2014). Arsenic is a problem worldwide, more strongly in 3rd world countries like Bangladesh (the national standard for arsenic in drinking-water in Bangladesh is 50µg/L (Ahmad et al., 2018)). When water wells are made deep into the ground, the natural arsenic there can be disturbed and enter the drinking wells. Still, though arsenic is considered an issue in 1st world countries such as Canada or the United States of America (Schwarzenbach et al., 2010). One of the reasons is that arsenic is found in some pesticides that are being used and runoff from farms using these pesticides can go into water supplies and natural waterways. The number one reason for contamination of drinking water in more developed countries is mining tailings, primarily gold mining, as disturbing the ground that deep can allow for arsenic to be released into natural waterways. This is only projected to worsen as more mines are opened internationally to meet rare earth metal demands (Vladimir, 1990).

1.2 Paper Structure

This design report will first start with an introduction of literature review on the different detection and filtration methods considered for the project. Then the method of selection used for both the detection type for which the software is made, and the filtration method will be discussed and described. This is then followed by an explanation of how the detection software and filtration design was implemented. Then the results from the software and filter are shown, followed by a discussion of the results and suggestions for recommendations to get more accurate results. Next is a description of the cost breakdown of the filtration and detection software. Finally, the paper will end off with the conclusions on the work done for this project and will be followed by the references and supplementary materials.

2. Literature Review

2.1 Detection

Due to variables that apply limitations on the scope of the project, detection was achieved through a pre-produced kit rather than a newly innovated one. This led to the primary focus of the design project to be on the novelty of an easy and accessible colour detection software method to ensure accurate reading in the field when using colour based tests (optical-chemo sensors). The following section details both traditional and current innovative forms of testing for arsenic that were considered for this design project so that the software was made with a focus on the most easily accessible, cheap and easy to operate detection method. There are two major categories of detection of arsenic for water, the first being methods that can be performed in a lab and the second, the one most applicable to this project, being those that can be done in the field. Methods done in the lab are accurate but typically are costly, take a long time, and are not convertible to robust in field forms where the testing is needed most. Field methods are problematic in that current methods have been known to be inaccurate, inaccessible (due to price and ease of use) and at times lack the robustness necessary for the field.

2.1.1 Lab methods

Lab methods do test well below the WHO detection limit but in trade these methods for analyzing arsenic require properly trained staff and expensive and complex tools and facilities. These methods are also quite time intensive, making them unsuitable for field testing or for repeated testing for research or routine checkups. These methods include various forms of: Atomic absorption spectroscopy (AAS), Atomic fluorescence spectrometry, inductively coupled plasma (ICP), ICP/mass spectrometry (MS), Atomic Force Microscopy (AFM), Surface Enhanced Raman Spectroscopy (SERS), Neutron Activation Analysis (NAA), Capillary Electrophoresis (CE), Surface Enhanced Raman Spectroscopy (SERS) and Laser-induced Breakdown Spectroscopy (LIBS) (Luong et al., 2007).

2.1.2 Field Methods

2.1.2.1 Electrochemical

Electrochemical methods are desired due to their ease of portability and low cost. According to Luong et al. (2007) the following methods are ideal for testing as(III), but for the testing of As(V) it must be reduced to As (III). The most popular reductant to do this is potassium iodide which is then used in conjunction with ascorbic acid to prevent oxidation of iodide to triiodide by air. Low-cost methods available using electrochemical methods include polarographic techniques, cathodic stripping voltammetry (CSV) and anodic stripping voltammetry (ASV). Polarography (Linear Sweep Voltammetry (LSV) at the Hanging Mercury Drop Electrode (HMDE)) is considered an outdated technique with limited detection ranges between 10ppb and several ppb. CSV has a more enhanced sensitivity than direct polarography but due to multiple chemical interferences, makes it hard to get good detection limits. ASV is a method that is based off the following deposition of arsenic on the electrode surface followed by anodic stripping:

$$\text{Deposition: } As^{3+} + 3e^{-} \rightarrow As^{0}$$
$$\text{Stripping: } As^{0} \rightarrow As^{3+} + 3e^{-}$$

This method has multiple types of electrodes including microelectrodes, platinum nanoparticles, and boron. Ultimately though this method, as seen with the current available field apparatus the Nano-Band™ Explorer suffers from sensitivity issues when other heavy metals or introduced or other species such as water surfactants are contained within the sample (Luong et al., 2007).

2.1.2.2 Optical Chemo sensors

This is a broad category of sensors that can be used for the detection of arsenic. They are defined as sensors that use a light source as a delivery or collection medium for signal transduction mechanisms like change in absorbance, color, luminescence, and dynamic light scattering (Devi et al., 2018). They are considered a promising group of sensors as they are generally considered easy to use, low cost and have the possibility to test for multiple contaminants at once. There is significant research regarding these types of sensors and materials that can be used to make them. Devi et al. (2018) in their paper go into detailed study of the meta-analysis of this method and suggest that they offer advantages due to their simple hardware, the higher sensitivities and their field portability (Devi et al., 2018).

2.1.2.2.1 Paper based Sensors

This popular category of sensors involves using a piece of paper impregnated with some type of substance that when chemically reacting will change colour to indicate a concentration or presence of the substance being tested for. These methods are affordable, portable and easy to use. Some methods available in testing kits have had issues, which can be seen in section 2.1.3.1 when discussing Hydride generation. Another impregnating material being explored for paper-based sensors is the use of gold nanoparticles. Not much work has been done with this method for commercial use, but it is shown to be a potential good method. This method works by impregnating a strip of paper with a gold nano-particle solution. When the gold nano-particle solution meets arsenic, it changes colour to indicate the concentration of arsenic present. This is a favourable method as most research has shown that methods using gold nanoparticles have a sensitivity well below WHO recommended levels. Using gold nanoparticles is also cost effective per single test, quick, easy to use, can use biodegradable filter strips and does not cause environmental hazards, like arsine gas, that other popular methods are known to do (Devi et al., 2018; Luong et al., 2007). There are multiple methods to synthesize the solution and use the solution. Most of these methods start with chloroauric acid ($HAuCl_4$) which is then reduced using some other reagent which is dependent upon the method chosen. The most popular method is the Turkevich method which uses trisodium citrate, but many other methods can be used to achieve the same effect (Vikman, 2018). The selection of the gold nanoparticle method considered is discussed more in depth in the method and design approach section of this report.

2.1.2.2.2 Bio-conjugated Nanomaterials and Biosensors

This group of sensors involves the use of biological substances such as DNA, RNA, and enzymes as a base for the sensor. There is a large variety of methods for synthesizing and use of detection dependent on the base chosen. They all have the same method in requiring a reaction between the contaminant and biological material, and depending on the reaction observed, data can be extracted for the detection of arsenic. This method is considered to allow for high specificity, selectivity and sensitivity. The most commonly used bases, which are used in whole cell forms, are aptamers and peptides but it should be noted that reporter genes, lipoic acids and fungus synthesized are becoming more popular in current studies (Devi et al., 2018). This category of sensors struggles with sensor stability, cell viability, material stability and the need for controlled operational conditions.

2.1.2.3 Current Test Kits

Test kits currently are efficient in detecting high levels of arsenic but are problematic when lower levels are concerned. There have also been multiple reports of inaccurate tests and false negatives, causing arsenic poisoning to occur even after testing (Luong et al., 2007).

2.1.2.3.1 Hydride Generation

As discussed in the meta-analysis performed by Luong et al. (2007), this method is considered the most popular for inorganic detection using the "Gutzeit" method. Zinc powder is typically used as a reducing agent for As(V) and As (III) to arsine (AsH_3) which goes through mercuric bromide impregnated paper. The reaction is the following:

$$As_4O_6 + 12\,Zn + 24H^+ \rightarrow 4AsH_3(gas) + 12\,Zn^{2+} + 6H_2O$$

$$Zn + 2H^+ \rightarrow Zn^{2+} + H_2\,(gas)$$

This method uses a colour comparison of the colour change that goes from white to yellow to brown. The hydride generation reaction (limiting reaction) can take anywhere from 10-30mins which is dependent on the reagent used. An alternative to this method is the arsine generated can be passed through paper impregnated with lead acetate before reaching the mercuric bromide. Due to estimations of the limit detection being based on colour visualization they cannot be confirmed much with lab results. This method also has the added side effects of creating toxic mercury solid waste and highly toxic arsine gas above the threshold limiting value of 0.05 ppm volume by Occupation Safety and Health Administration (OSHA). Therefore, although this method requires little training, time and cost, it is not seen as a desirable method (Luong et al., 2007). Tests have been done with other methods such as using silver nitrate, using arsine gas to bleach a dye, and having arsine gas pass through a permeable membrane for it to be oxidized and transformed into its molybdenum complex. However, these methods only test well in concentrations well above the WHO recommended level and experience interferences when other metals or compounds are involved (Devi et al., 2018).

2.1.2.3.2 Colour Differentiation and Visual Aid Devices

A majority of kits rely on optical identification of colour change in order to detect the concentration of arsenic in the water sample. Most kits rely on a colour identification card that users hold up to their paper sample when the chemical colour change reaction is finished. The user must correctly match the sampled colour to the provided colour identification card in order for testing to be successfully completed. This has created some issues in accuracy of readings as different shades of colour can be hard to differentiate depending on multiple factors such as lighting and the users eye site and natural colour differentiation ability. There has been a recommendation to investigate and create visual aid devices in order to mitigate human errors when using colour-based detection techniques. Recommendations have included the use of completely separate handheld devices such as independent devices like hand-held scanners and digital readers, or the modification of mobile apps and GPS tools (Devi et al., 2018). This research is considered to be in its nascent stage as described by Devi et al. (2018), but there is some promising research available on mobile application creation as done by Shrivas et al. (2020). They were able to produce an app using ImageJ software to create an app for smart phones in order for colour intensity detection. This is a promising technique and will be discussed more in the method and design approach section of this report (Shrivas et al., 2020).

2.2 Filtration

Arsenic contamination of drinking water is a huge concern. Finding a filtration method and in turn a filter that is efficient at removing a good amount of arsenic from drinking water is an issue that is of importance. There are many filtration methods currently available to remove arsenic from water. These methods work under specific conditions and each have unique factors to consider ensuring maximum arsenic removal. The commonly used techniques are oxidation, membrane technologies, coagulation/flocculation, adsorption and Ion exchange (Nicomel et al., 2016). Other methods like phytoremediation and electro-kinetics have been recently used but are not very developed (Singh et al., 2014). In this review, we studied each of the commonly used methods, taking into consideration the arsenic removal efficiency, ease of use, cost, and portability in order to decide which methods were most compatible for our design.

2.2.1 Oxidation

Oxidation involves converting soluble arsenite (Arsenic (III)) to arsenate (Arsenic(V)). This method does not remove the arsenic from the water directly, and thus an extra technique like adsorption, needs to be followed to take out the arsenate (Nicomel et al., 2016). This is important especially because in underground anaerobic water, As(III) is the most present (Masscheleyn et al., 1991). Atmospheric oxygen, hypochlorite, other chemicals as well as bacteria can be used to directly oxidize the water (Nicomel et al., 2016). Selecting the proper oxidant is essential in ensuring enhanced oxidation and reducing the effects of interfering substances present in the water. In a study by Hellweger and Lall (2004), they showed that solar light oxidation of As(III) is suppressed by algae in water with high microbial activity (Hellweger and Lall, 2004). Oxidation is a relatively simple process, has a low operational cost, and is applicable for large volumes of water. Issues with oxidation is that toxic chemicals and carcinogens are produced as by products, there can be interfering substances that reduce the removal efficiency, and there is an additional step required (Mondal et al., 2017). These drawbacks of the method when weighed with our choosing criteria make it not the most suitable for our design. Thus, we decided not to use oxidation as our technique of filtration.

2.2.2 Ion Exchange

Ion exchange occurs by the exchange of an ion on the solid resin (an elastic three-dimensional hydrocarbon network that contains a large number of ionizable groups which are joined together electrostatically) phase for one in the contaminated water (Singh et al., 2014). The ion in the contaminated water has a similar charge to the one on the solid resin, and they have a stronger selectivity for the resin. As removal is typically done by strong base anion exchange resins, As(V) in its oxy-anionic state such as dihydrogen arsenate (H_2AsO^{4-}) is exchanged with the anionic charged functional group of the resin, producing an effluent that has a low concentration of As(V) (Choong et al., 2007). As the resin becomes depleted, it needs to be regenerated (it can be done by washing with a NaCl solution) (Ahmed, 2001). Arsenite is not removed by the process because it is uncharged (Singh et al., 2014). Thus, pre-oxidation of As(III) to As(V) is carried out. This pre-oxidation increases the efficiency of the ion exchange process because more As is removed when the As(III) is initially converted to As(V) (Ahmed, 2001). In order to avoid the effect of sensitive resins the oxidant has to be removed before ion exchange. Thus, the concentration of competing ions (mostly sulfates and nitrates), and type of resin affect the efficiency of the ion exchange for As(V) removal (Ahmed, 2001). Also, the amount of total dissolved solids (TDS) in the water reduces the efficiency of the ion exchange process (Singh et al., 2014). This shows that the ion exchange technique is more efficient in a low sulfate, low TDS water medium. Iron 3+ ions may also form complexes with As(V) if present in the water. These complexes cannot be removed during the ion exchange process (Singh et al., 2014). Thus, the presence of Fe (III) in the water reduces the efficiency of the process. Therefore, although the ion exchange process is not significantly pH sensitive and leads to removal of a moderate amount of arsenic from drinking water, the pre-oxidation step required for arsenite removal, sensitivity to competing ions and regeneration of the resin (leads to production of a toxic substance which is not environmentally safe) make this method not a suitable choice as a filtration technique.

2.2.3 Membrane Technologies

Membrane filtration involves the use of membranes for the removal of arsenic and other water contaminants. The membranes are typically synthetic materials acting as a barrier which selectively allow some materials to pass through while preventing others. The membranes have pores to allow movement of some substances through it. The movement across the barrier needs a driving force like a pressure difference to transport the water through the membrane (Shih, 2005). There are two main types of membrane filtration techniques: Low-pressure membrane processes for example microfiltration and ultrafiltration, and high-pressure membrane process like reverse osmosis and nanofiltration (Nicomel et al., 2016). These processes have different characteristics which we will discuss in this paper.

2.2.3.1 Low-Pressure membrane processes

Microfiltration is used to separate particles in the range of 0.1 to10μm (Nicomel et al., 2016). It is not effective to use this method alone to remove both dissolved arsenite and arsenate species from contaminated water, as some of it may pass through the membrane. Thus, in order to use microfiltration, the size of the arsenic species has to be increased (Singh et al., 2014). This can be done by coagulation and flocculation processes which we will discuss later in this paper. In a study by Han et al. (2002), they showed that arsenic removal rate was higher when a combination of flocculation and microfiltration were done than when microfiltration was done alone (Han et al., 2002).

Ultrafiltration is a membrane separation process at low pressure where the membrane has pore sizes in the range of 1 to 100nm (Singh et al., 2014). Ultra-filtration alone is not effective for arsenic filtration. Therefore, like microfiltration, in order to use ultrafiltration, surfactant-based separation processes can be used (Nicomel et al., 2016). A technique that is commonly used is micellar-enhanced ultrafiltration (MEUF). Although adding the surfactant leads to higher arsenic removal, studies show that the concentration of the surfactant in the effluent is sometimes so high that the effluent needs further treatment before it can be released into the environment (Nicomel et al., 2016). Also, this method of filtration is pH sensitive, and it has been shown that a decrease in pH leads to a decrease in arsenic removal efficiency by this method (Nicomel et al., 2016).

2.2.3.2 High-Pressure membrane processes:

High pressure membrane filtration techniques like nanofiltration and reverse osmosis require a high pressure to push the substance through the membrane.

Nanofiltration can significantly remove arsenic from drinking water provided the drinking water contains low amounts of suspended solids (Figoli et al., 2010). The size of the membrane pore is about 1nm (Singh et al., 2014). Considering the amount of pressure that this method requires, it is energy intensive and thus, expensive. It also requires high capital and running cost (Ahmed, 2001).

Reverse osmosis is the most effective of arsenic removal from water for small treatment systems. The membrane pores are very small (<0.001µm) (Schneiter & Middlebrooks, 1983) and the process can be easily automated and controlled. The process is more effective when the arsenic species present is arsenate, and when the water is free of suspended solids (Nicomel et al., 2016). This process is also very expensive, and energy intensive. It also requires high technical operation and maintenance (Ahmed, 2001).

The low-pressure membrane filtration techniques require an extra step and do not have a very high As removal efficiency, so we chose not to go with either of them. Although both high-pressure techniques have a good arsenate removal efficiency and do not lead to the production of any toxic solid waste, they are highly energy intensive, have a high cost to operate and maintain, and pretreatment steps are often required. Also, arsenic removal efficiency is very low when the arsenic contaminated water has a high concentration of arsenic. These reasons made us decide not to use either of the high-pressure membrane techniques.

2.2.4 Coagulation/Flocculation

Coagulation-flocculation are common methods of water filtration. It involves the addition of a coagulant, followed by the formation of flocs. The positively charged coagulant reduces the negative charge of the colloid in the water thus making the particles collide and get larger (Singh et al., 2014). Flocculation involves addition of a negatively charged flocculant that leads to charge neutralization between the already formed large particles thus leading to flocs formation

(Nicomel et al., 2016). Some common coagulants for As removal are Iron-based coagulants and Aluminum based coagulants. Iron-based coagulants have a higher arsenic removal efficiency because iron hydroxides have a lower tendency to go into solution and have a strong affinity to arsenic especially As (V) (EPA, 2015). The chemicals transform the dissolved arsenic in the water into an insoluble solid which can later be precipitated. The solids can then be removed by filtration or sedimentation (Nicomel et al., 2016). Arsenic removal efficiency using this method depends on the coagulant and flocculant chosen. With the appropriate choice of coagulant and flocculant, pH is not an issue (Singh et al., 2014). This process is also relatively cheap and simple to operate, and large volumes of water can be filtered using this method. A major drawback of this technique is the formation of arsenic contaminated sludge. Treatment of this sludge is costly and if not properly managed, the sludge can lead to environmental pollution (Ahmed, 2001). Also, an extra step which is required to separate the filtered water. We decided to study this method more to see if we could find an alternative way of handling the sludge and look at possibilities of increasing arsenic filtration based on our choice of coagulant/flocculant.

2.2.5 Adsorption

Adsorption uses solid adsorbents to remove substances from water. The substances are removed from the water and accumulated at the surface of the sorbent (Nicomel et al., 2016). Electrostatic forces and Vander Waals forces are the main driving forces in this process between the adsorbate molecules and the adsorbent thus, the properties of the adsorbent of choice are very important (Choong et al., 2007). Several adsorbents like activated carbon, sand, biochar, and iron-based sorbents have been used to remove As from drinking water (Singh et al., 2014). Some of these adsorbents are significantly developed and commonly used while others still need more development and testing. Adsorption is a great method of As removal from drinking water because it has a high arsenic removal efficiency depending on the choice of adsorbent, it is low cost, simple to operate and maintain, and does not lead to sludge formation.

Drawbacks of this method are competition between pre-existing ions and the efficiency of As removal is pH sensitive. These drawbacks can be managed based on the choice of adsorbent, thus we decided to go with adsorption as our second choice, study it in more detail and decide on an appropriate adsorbent that significantly manages the drawbacks.

2.2.6 Comparison between Adsorption and Coagulation-Flocculation

From the review above, we decided to go with coagulation-flocculation and adsorption and compare both techniques in order to choose the most appropriate filtration technique for our design. We also came up with a Pugh chart (Appendix 3) comparing these methods to see which of them was better for our design.

Coagulation/flocculation is effective and simple, but issues of concern are high doses of coagulant needed and disposal/treatment of sludge formed with this method. Cost and environmental sustainability are two important criteria of our design, thus, buying these coagulants at higher doses may be an additional cost, and disposal of the sludge may be an issue for the environment. Disposal/treatment of the sludge may be an issue long run if we decide to go with this method. Coagulation/flocculation also has an additional cost as an extra step is necessary for water filtration after coagulation/flocculation.

Adsorption, although is an efficient method for arsenic filtration, is highly pH sensitive and affected by the presence of co-existing ions. These issues with the method are dependent on the type of adsorbent used. Thus, choosing an appropriate adsorbent is essential. There are adsorbents that can handle these problems, making them less of a concern. For example, arsenic adsorption by Iron based adsorbents is not significantly affected by the presence of common anions like as Cl^-, NO_3^-, SO_4^{2-}, CO_3^{2-} due to the specific chemical reaction between arsenic and iron (Linlin et al., 2018). Adsorption is also easy to operate, handle and easy to set up as a point of use As removal technique (Jang et al., 2008). At the household small scale level, this method is a good filtration technique.

Considering these reasons and the weighting of adsorption which can be seen on our Pugh chart, we chose to go with adsorption as our method of filtration.

2.2.7 Adsorption – Adsorbent

Based on the review, adsorption was chosen as the filtration method. Adsorption is an efficient method, is cost effective, and easy to operate. Although it is pH sensitive, we can find an adsorbent that works in a pH range for effective adsorption of both arsenite and arsenate. Arsenate adsorption is high at a pH below 7 (Zhu et al., 2013) while arsenite adsorption is high at a pH between 4 and 9 (Nicomel et al., 2016). Thus, finding an adsorbent that is efficient within a pH range of 4-7 will favour both forms of arsenic adsorption.

There are many adsorbents which are currently being used to remove arsenic from water. Most of these methods are not very effective because of pH sensitivity and competition from existing ions (Yadanaparthi et al., 2009). These adsorbents can be group under different categories like activated carbons and activated alumina, non-conventional low-cost adsorbents (like bio adsorbents, agricultural products and by-products, and industrial by-products), metal-based methods (like iron-based methods) and nanomaterial adsorbents (Singh et al., 2018). Composites of these adsorbents have also been made and used to test the extent of arsenic removal from drinking water. The most commonly used one is activated carbon, and most adsorbents are compared to this (Singh et al., 2018). We studied each of these categories of adsorbent based on cost, availability, selectivity of the sorbent, competition with coexisting ions in arsenic contaminated water and effects of pH (pH range in which the sorbent is most effective) and decided to focus on two main types, non-conventional low-cost sorbents specifically biochar and iron-based adsorbents.

Activated carbon is a strong adsorbent and has been widely used for arsenite and arsenate adsorption from water. It is highly porous and has a good surface area (300 – 2500m^2/g). The large number of pores make it have a large inner surface which makes it a great adsorbent. However, activated carbon is not the best option for removing some anionic contaminants because of the negative charge on its surface (Cooper et al., 2010). Recently, composites of activated carbon and other adsorbents have been made to increase efficiency of arsenic removal (Chang et al., 2010). Although this has been done, activated carbon is still not the most-effective method of arsenic removal from water as the production process of activated carbon is expensive (Hjaila et al., 2013). Also, activated carbon is not very environmentally friendly. Thus, although it is the most common adsorbent presently used for arsenic adsorption from water, it was decided to continue research on finding an alternative cost-efficient sorbent that has less environmental impacts.

Nanomaterial adsorbents have recently been studied for arsenic adsorption from drinking water due to their high specific surface area, high specificity and high reactivity (Hristovski et al., 2007). They are novel adsorbents thus more studies are still being done on them. Examples of widely used nano particle adsorbents are iron-based nanoparticles, titanium-based nanoparticles and carbon nanotubes (Nicomel et al., 2016). A drawback of using nanoparticles is that they have high surface energies, thus they tend to aggregate when they are in aqueous media. This leads to a decrease in their surface area, and a reduced capacity and selectivity which results in a decrease in the lifetime of the process and thus potential to use in real life applications (Nicomel et al., 2016). Due to this, it was decided not to use nano material adsorbents as our adsorbent.

Using low-cost adsorbents like agricultural products and by-products is environmentally friendly as we will be using materials that are easily available, and do not cause any effects to the environment. Agricultural products like wood chips, and agricultural waste like rice husks, orange peels have all been tested for arsenic adsorption from water (Mohan, 2007). Most of these materials are converted to biochar and then tested for arsenic removal. The biochar is a good substitute for activated carbons, are inexpensive and locally available (Singh et al., 2018). An issue with using plain biochar for arsenic adsorption is it is not the most effective at removing arsenic from water, that is the arsenic removal efficiency is low (Hu et al., 2015). Recently, composites have been made to remove more of the arsenic as is the case with activated carbon. Studies suggest that there is a high potential for arsenic filtration from water using these composites (Hu et al., 2015; Tchomgui-Kamga et al., 2009). Considering the huge advantages of using this method, it was decided to do more studies on it and look at composites that could be appropriate for our design.

Metal based methods have also been used recently. Iron-based adsorbents are widely used because they are a safe and simple method of removing arsenic from water (Linlin et al., 2018). They also have a high removal efficiency of arsenic, are environmental friendliness and easily accessible (Linlin et al., 2018). Most common iron-based adsorbents can be chemically synthesized by the precipitation of iron 3+ or iron 2+ salts through hydrolysis and oxidation processes (Linlin et al., 2018). A commercially available form of these is granular Ferric hydroxide. With iron-based adsorbents, common anions such as Cl^-, NO_3^-, SO_4^{2-}, CO_3^{2-} do not have a significant influence on arsenic adsorption due to the specific chemical reaction between arsenic and iron (Linlin et al., 2018). Iron-based adsorbents like iron oxyhydroxide and other metal-based adsorbents have been combined with activated carbon and biochar to form composites with a higher arsenic adsorption efficiency (Singh et al., 2018). Considering these advantages of using iron-based adsorbents, it was decided to study more about them, and look at the possibility of using them for our design.

Iron-oxyhydroxides have been used to make composites with activated carbon and biochar. According to a study by Samsuri et al. (2018), iron loaded biochar has been shown to adsorb almost 2~8 times more arsenic than plain biochar (Samsuri et al., 2018). Thus, since we are considering biochar, we looked at the possibility of using a composite of biochar and Iron-oxyhydroxide as our adsorbent. Appendix 4 shows a Pugh chart where we compared biochar, iron-based adsorbents and iron loaded biochar (composite of biochar and iron loaded) to decide on the most appropriate adsorbent.

Based on the results from the Pugh chart (Appendix 4), the possibility of handling the pH sensitivity based on the choice of biochar, and less competition from competing irons (iron-based adsorbent), we decided to choose iron-loaded biochar as the adsorbent for our filter. Iron-loaded biochar is also good adsorbent because it adsorbs more arsenic than pure iron-oxyhydroxide and regular biochar.

Biochar material

There are many materials that we can make biochar from. We chose and narrowed down the possible materials based on studies where biochar has been used, the pH range of water at which each of these biochar materials are effective, the ability to remove both forms of arsenic, and the ease of getting the material. Arsenic exists in water in the form of As (III) and/or As(V), with pH of the contaminated water within the range of 6-9. Arsenite removal from water is high within a pH range of 4-9 while arsenate removal is high within a pH below 7 (Nicomel et al., 2016). While choosing the biochar, we took into consideration this pH ranges, and chose a material that is effective within a range of 4-7. This was chosen in order to reduce the effect of pH sensitivity, thus choosing a material that offers higher adsorption possibilities. This led us to narrow down to three main options which are wood chips, wheat straw and rice husks.

We decided to go with pine wood biochar because it is easily accessible in any region, has a good pH sensitivity and studies by Mohan et al., (2007) show that they have an adsorption capacity of 0.0012mg/g for arsenic in drinking water at concentrations between 10 - 100µg/L, which includes the WHO MAC of arsenic in drinking water (10µg/L) (Mohan et al., 2007). Wood char absorbs contaminants from water because of its porosity (Lou et al., 2011). Modifying the pine wood biochar with an iron salt will increase the efficiency of adsorption, and there by make it an option to be used as a good adsorbent for the filtration of arsenic in drinking water

3. Design

3.1 Design criteria

3.1.1 Technical

The technical aspect of the project is to ensure that the detector software is efficient and accurate in reading results from of the detection, and the filter is efficient at filtering out a good amount of the arsenic to below the maximum allowable levels for drinking water.

3.1.2 Social

The social concern involves choosing an appropriate filter/detector software that works, is easy to use and at the same time is environmentally safe. Combining both or prioritizing one over the other is a constraint. We are trying to choose an option where both are attained.

3.1.3 Environmental

The main environmental criterion is to choose an appropriate filtration technique where the waste after filtration which involves arsenic and other chemicals, is disposed of efficiently, and poses no threats to the environment.

3.1.4 Economic

The economic criterion focuses on in designing a system that is affordable especially for smaller communities who are mostly found in areas with serious arsenic contamination. We hope to design a system that is efficient yet affordable.

3.2 Chosen method of Detection and Concentration Identification

The chosen method of detection was to use a pre-made kit that uses the hybrid generation technique mentioned in the literature review. Concentration identification is achieved through colour matching using ImageJ and excel to create a streamlined method of accurately interpreting the results from the kit. The following section will detail how these methods were chosen and how it will be implemented.

3.2.1 Sensor/Detector

The goal of the detector is to ensure that proper detection of arsenic occurs. Due to the limited time and lack of expertise of the team, it was decided that the innovation of the detector would lie in the interaction between the filter and detector for optimization, not within the detection system itself. In order to achieve this an existing product on the market was chosen.

3.2.1.1 Sensor/Detector Selection

The decision to buy pre-existing tests on the market came after discussing the limited budget for this project and what is currently available. As mentioned before, the goal of the detector is not to be an innovative new method, but rather the innovation is in the extended application of the detector by allowing it to help optimize the use of the filter. Though it is considered more optimal to use a method that is not necessarily in the market and has been researched to improve upon current market available products and has room for innovation and ingenuity through industrialization, the limitations of project had to be considered.

The test chosen was the Quick Arsenic Mini Kit that uses a modified Gutzeit Method patented to the company. This was selected as it was within the price range, would arrive within a reasonable amount of time, provided plenty tests for our needs, and tested well below the minimum arsenic concentration that is the goal to filter out. The goal was to achieve the WHO and USEPA maximum concentration of 10 ppb and the Quick test kit test can detect as low as 0 ppb.

3.2.1.2 Sensor/Detector Methods and Design

Tests were done according to the directions provided within the kit for specifically water tests which can be referenced in Appendix 9.

3.2.2 Visual Aid Device

As mentioned previously, software to support users in correctly colour matching their results in order to select the correct concentration of arsenic is crucial. It also helps with identifying more specific concentrations that are not easy to determine between intervals displayed on colour test cards provided in kits. It was decided that this will be an added feature in the project as part of the innovation of this design as unlike other filters, it is optimized for use in the field and is easy to use. In order to achieve this, it was decided that a combination of ImageJ and Excel would be used to help users correctly identify the concentration their testing strips indicate. The following section will detail the selection criteria and plans used for the software.

3.2.2.1 Software Selection

The plan to use ImageJ is based on research done by Shrivas et al. (2020) where they developed and researched software using ImageJ software that takes a smart phone captured photo and processed the information in order to determine the colour intensity and therefore the arsenic concentration. This is the most concise use of colour matching research involving arsenic that is currently available and was proven successful in their work and was therefore chosen for this project. Unlike Shrivas et al. This project uses ImageJ for identification of the blue value of the red green blue (RGB) values instead of using a colour intensity as it is not clear how Shrivas et al. use ImageJ to properly determine colour intensity. Excel was also selected to use as the calibration software as it is an easy and accessible spreadsheet software that allows for a wide array of graphing tools. Any alternative spreadsheet software such as Google sheets may also be used.

3.2.2.2 Visual Aid Device Methods and Design

RGB identification is done using ImageJ and the calibration and colour matching is done in Excel. This method can be used with any type of colour strip test. An example excel sheet from testing can be seen in Appendix 7**.**

Lighting and Instructions for Picture Taking:

All photos must be taken under the same lighting, preferably with an opaque solid background, such as a piece of plain white paper, in order to help identify the subject matter clearly and consistently. The lighting requirements of the testing strips as instructed in kit instructions must be considered first as some strips are sensitive to different types of light. Directly under a light emitting diode (LED) light or natural sunlight is recommended if possible. Taking all the photos of the tested samples within a small-time interval will help ensure a consistent lighting environment and help eliminate any errors in colour identification due to changes in lighting or environment. Two sets of photos will be needed, the first set is of each individual colour on the colour identification card provided in the testing kit and the second set is pictures of the testing strips after testing.

ImageJ for RGB Identification:

ImageJ is a free open-source software and is a simple download from the ImageJ website. After downloading the appropriate software to a computer, no extensions are needed. It is recommended that the file ImageJ Basics available on the ImageJ website is reviewed before attempting to use ImageJ to familiarize oneself with the software layout and functions. The photo of the testing kit identification strip can be taken as one photo and then each colour can be isolated and analyzed separately.

The method used to identify the red green blue (RGB) identification is basic intensity quantification, as instructed by steps outlined by Christine Labno from the University of Chicago (Labno, n.d.). Labno describes multiple methods to quantify RGB values and other values, but the method to be used will take a measure of the RGB values over a certain area. To do this a region of interest (ROI) must be drawn first. To draw an ROI a drawing tool needs to be selected from the toolbar and used. Different shapes can be selected to draw the ROI, but a rectangle is typically the easiest and recommended shape to use. Then use the following order to separate that area from the primary image: Analyze, Measure (will limit the RGB measurement to the ROI area), Edit, Selection, Restore Selection. If this does not work, right clicking the ROI and selecting duplicate, then ok (renaming the file isn't necessary) will have the same effect and will allow for the ROI to be automatically put in a separate window after clicking. At this point the ROI area will be separated into another image to analyze just that area (Labno, n.d.).

To get the information of the isolated section, redraw the ROI in the new selected section and now click Plugins then Analyze then RGB Measure and it will measure the RGB values of the selected ROI (Labno, n.d.). The mean blue value of the RGB value types is the value to be taken as it was found in previous testing on multiple colour samples that blue was the most linearly related between lighting types and therefore the least influenced by lighting environmental changes. Select graphs from this testing can be seen in Appendix 10 which were performed using the colour identification card from the testing kit used in this project.

Excel Calibration:

Calibration is necessary for creation of a line of best fit for analysis. This line of best fit is created from the blue RGB values from each colour on the testing kit identification card. Once each colour is identified the numbers are put into an excel sheet and then used to make a X-Y scatter plot. The Y-axis representing the original colour concentration indicator and the X-axis indicating the mean blue RGB value intensities from the colour indicator card. From this the equation of this best fit line can be found, linear or polynomial are recommended. A blank template of the spreadsheet ready for plotting that can be seen in Appendix 7 can be provided for users who are not familiar with Excel.

Identification:

Identification is done by finding the blue RGB value of the tested sample and then using it as an x – value in the equation found from the line of best fit to identify the concentration numerically. This method allows for identification of approximate concentrations between given intervals provided on the colour indicator card.

3.3 Filtration Design

The filter design is a combination of the cartridge, adsorbent, receiving container to collect the filtered water, and a container at the top to hold the water before it passes through the cartridge. This design is similar to a pitcher filter. The filter design type is chosen because arsenic contamination is mostly found in groundwater, thus, choosing a faucet filter where the cartridge is attached to a faucet is not the most applicable especially in small communities mostly affected by arsenic contamination of water where the groundwater is directly collected from the ground through wells and boreholes. The materials needed for the filter can be divided into three categories, the cartridge, receiving containers, and adsorbent. Each of these materials will be discussed below.

3.3.1 Materials

3.3.1.1 Cartridge

The cartridge chosen for the filter is the refillable cartridge. This cartridge falls under the category of carbon cartridges, making it suitable for use with the adsorbent: biochar. With this cartridge, water flows from one end through the length of the adsorbent inside, then flows out through the other end maximizing contact between water and the adsorbent. This type of cartridge is effective at removing chemical contaminants and is thus a good choice for removing arsenic from drinking water. The cartridge can be transparent or opaque and provides flexibility to the user where they can simply change the adsorbent when it is time for replacement. A standard white 2.5 inches by 10 inches empty refillable cartridge made by hydronix was purchased from amazon. Most of the products from hydronix are NSF (National Sanitation Foundation) international certified to NSF/ANSI (American National Standards Institute) standards (Hydronix, 2020; NSF international, 2012). This cartridge is made from high impact polystyrene (used to make other granular activated carbon filters at hydronix which are

NSF/ANSI certified) and contains polypropylene pads at each end (prefilter and postfilter) which provide sediment filtration and prevents media from being released by the cartridge (Hydronix, 2020). Methods of optimizing the cartridge were researched but not designed physically due to limited time and resources.

The main method that was considered to optimize the cartridge is by adding a mesh material package to the cartridge to hold the media. During testing, some of the media got trapped in the polypropylene pads at the ends of the cartridge. Removing these pads was not very easy and some users would not like the amount of contact necessary to take out and replace these pads because the pads may be contaminated with arsenic especially if it has been used for long. Adding a removable mesh-like material that has a diameter smaller than the diameter of the biochar adsorbent media will ensure that the media stays in the mesh like material, is easily disposable and does not require much contact to take out. The material can be made from polypropylene like the pads. More research needs to be done to see how this material can be made. How the cartridge works with this material is that the biochar gets filed into this material, and after use the material is disposed with the biochar in it, then the cartridge is cleaned and another mesh like package is put into the cartridge and biochar added in this. Using this material will also prevent any media from being released by the cartridge.

3.3.1.2 Receiving containers

The receiving containers can be made of standard filter glass or plastic depending on the needs of the user. Most water filter vessels nowadays are made from BPA (bisphenol A) free plastic, this could be an alternative. A high standard BPA free plastic can be use, or another alternative is to use glass for the vessel. Plastic is cheaper, and easy to use in most small communities that have arsenic contamination of water problems so this may be the most feasible choice of material to use.

3.3.1.3 Adsorbent

The adsorbent of choice for the filter is a composite of iron loaded biochar. This adsorbent is chosen based on its efficiency at removing arsenic, and other reasons discussed above. The biochar is in the powdered form, and a focus is on ensuring that the diameter of the biochar is larger than the size of the pores of the polypropylene pads in the cartridge, so the media does not pass through it. The iron loaded biochar composite is made using a method similar to the methods used by Xu et al. (2015), Micháleková-Richveisová et al. (2016) and Tchomgui-Kamga et al. (2009) for iron impregnation of biochar post pyrolysis. The chemical reaction is a hydrolysis reaction of the iron salt. The reaction is

$$\underset{\text{Iron nitrate}}{Fe\,(NO_3)_3} + 3H_2O \Rightarrow \underset{\text{Iron oxyhydroxide}}{Fe\,(OH)_3} + 3HNO_3. \qquad \text{Xu et al. (2015)}$$

The materials and method used to prepare the adsorbent are discussed in section 3.3.1.3.1.

3.3.1.3.1 Preparation of adsorbent

Materials:

The materials used to prepare the iron-loaded biochar composite are pine wood biochar, iron salt, deionized water, and magnetic stirrer. The iron salt used is Iron (III) nitrate nonahydrate ($Fe\,(NO_3)_3{\cdot}9H_2O$), which was used in a study by Hu et al. (2015). In their study, Hu et al. (2015) recommend that a composite made from hickory chips biochar and this salt is efficient at removing arsenic from water (Hu et al., 2015). The biochar was bought from an online vendor. In our filter, we combine this iron salt with pine wood biochar, which is efficient at removing contaminants from water and is easily accessible in most communities.

Method:

To prepare the adsorbent, a method similar to that used by Hu et al., (2015) was used. To get a higher amount of the biochar, we used more iron salt and more wood biochar than the study what was used in the study by Hu et al. (2015) but the final concentration of iron salt in the iron loaded biochar composite is the same as the one in the study. 36.15g of $Fe\,(NO_3)_3{\cdot}9H_2O$ was dissolved in 200ml of deionized water, forming an iron solution. This solution was mixed with 50g of the wood biochar and stirred for 12 hours using a magnetic stirrer (Hu et al., 2015). The resulting composite is then dried at 100 - 120°C. The composite was washed with deionized water to remove any surface hydroxide ions, and oven dried at 80°C, resulting in iron-loaded biochar (Hu et al., 2015). This process was repeated four times to get four different samples of the iron loaded biochar composite. During the washing and drying process, some of the biochar was lost, in total, we had a mass of 193g of iron-loaded biochar composite made.

3.3.2 Arsenic Solution

To test the filter, samples of arsenic contaminated water were made. The samples were made sample using a standardized solution of 100 µg/L of arsenic solution. Due to shipping delays and issues with getting this solution, a small amount (100ml) was gotten from the earth science department laboratory at McGill university, thus there was only enough for very small-scale testing to occur. With this amount, different solutions of arsenic contaminated water with different concentrations of arsenic were made. Section 3.3.2.1 shows calculations and the process of making the required concentrations of arsenic contaminated water for testing. After the solutions were made, a set-up as described in section 3.3.3 was made for testing.

3.3.2.1 Preparation of arsenic solutions

The original arsenic solution has concentration of 100mg/L, and volume of 100ml. The maximum allowable concentration (MAC) of arsenic in drinking water set by WHO is 10µg/L. In Bangladesh, one of the main areas affected by arsenic, the MAC is 50µg/L. The original plan was to make arsenic contaminated water solutions in a range that is above 10µg/L and above 50µg/L. Due to the limited amount of the standardized arsenic solution available, focus was placed on the WHO limit, thus the goal was adjusted to make arsenic contaminated water solutions above 10µg/L. Two arsenic solutions were made, one that is 20µg/L and another 40µg/L so we can test above the WHO limit and below but close to the limit in Bangladesh. These concentrations also allow to compare the efficiency of the filter when the concentration of arsenic is doubled.

Materials:

100mL of 100µg/L Arsenic solution, water, HDPE container with spigot, pipette, and Nalgene bottles for storing the contaminated water solution.

Method:

Initially, the standardized solution has a volume of 100mL and concentration of 100µg/L arsenic. The pipette has a volume of 10ml. The goal is to get 240ml of arsenic solution with a concentration of 20µg/L and 130ml of solution with a concentration of 40µg/L. Using concentration and volume, and the equation relating these two variables, we can solve for the amount of water to add to the standardized 100mL solution to get the required contaminated water.

Based on the molarity and dilution equation: $M_1V_1 = M_2V_2$ (Ball & Key, 2014)
Where M_1 and M_2 are the molarities (concentrations) of the standardized solution and required solution and V_1 and V_2 are the volumes of the standardized solution and required solution.

For the 20µg/L solution,

$M_1V_1 = M_2V_2$

$100\ \mu g/L \times V_2\ L = 20\ \mu g/L \times 0.24L$

$V_2 = 48mL$

192 ml of water was added to 48ml of the standardized arsenic solution to get 240ml of 20 µg/L of arsenic contaminated water solution. (Pipette used for measurements).

For the 40µg/L solution,

$M_1V_1 = M_3V_3$

$100\ \mu g/L \times V_2\ L = 40\ \mu g/L \times 0.13L$

$V_2 = 52mL$

78ml of water was added to 52ml of the standardized arsenic solution to get 130ml of 40 µg/L of arsenic contaminated water solution.

3.3.3 Filter Design Setup / Testing

A drawing of the set up for the tests can be seen in Appendix 5. Three different tests were carried out.

Test 1:

In test 1, 40g of the iron loaded biochar composite was measured and put in the cartridge. Due to delays in the shipping of the arsenic and the change in the scale of the project, the cartridge ordered was bigger than what was needed for the small-scale test being carried. Even though the cartridge was bigger, since the amount of biochar in the cartridge is known, there was still an opportunity to do the testing. 20g biochar was first added, then the cartridge then the cartridge was adjusted by shaking to add the remaining biochar. In total, we had 40g of biochar in the cartridge. It was closed, the put over the receiving vessel, and the collecting container placed on it. 120ml of the 20µg/L arsenic contaminated water was then passed through the filter and flows out through the other end of the cartridge into the receiving container. Not all the water comes out as some is lost in the biochar (it is used to compact the biochar). 100ml of water flowed out in approximately 91s.

Test 2:

In test 2, the same procedure was done as test 1. 40g of biochar was put in the cartridge as in test 1, and 120ml of the 40µg/L arsenic contaminated water was then passed through the cartridge and flows out through the other end of the cartridge into the receiving container. Not all the water comes out as some is lost in the biochar. 100ml of water flowed out in approximately 89s. This test was done to see if the concentration of arsenic affects the rate of filtration.

Test 3:

For test 3, we doubled the amount of biochar in the cartridge to 80g and tested the filtration efficiency using the remaining 120ml of the 20µg/L arsenic contaminated water. This test was done in order to determine if the amount of adsorbent affects the efficiency of filtration. The test was done similar to test 1. 100ml of water flowed out in approximately 99s, and not all the water flows out as in test 1.

4. Results

After the testing was done, an arsenic detection kit that was purchased was used to test for the amount of arsenic found in the filtered water. The procedure used for testing to see if any (the amount) of arsenic present as seen with the kit is shown in Appendix 9. The images gotten from the test can be seen in Appendix 7 and the results gotten from using the testing kit can be seen in table 1. The flow rate of the arsenic solution through the filter was also calculated using the formula below

$$\text{Flow rate} = \frac{\mathit{Volume\ of\ arsenic\ contaminated\ water\ solution}}{\mathit{Time\ taken\ for\ water}\ ¿}\mathit{flow\ through\ catridge}\ ¿$$

The values of the flow rate can also be seen in table 1.

Test number	Initial concentration of arsenic in water (μg/L)	Mass of biochar (g)	Final concentration of arsenic (μg/L)	Flow rate (L/s)
1	20	40	<5	1.098×10^{-3}
2	40	40	<5	1.12×10^{-3}
3	20	80	0	1.01×10^{-3}

Table 1: Results from testing filter.

The results gotten using the kit did not give a direct value for two of the tests as there was not a good colour match with the colour strip from the testing kit. Due to this, the results were analyzed using the software made in this paper in order to get a value for the arsenic concentration. The equation gotten using the linear line of best fit is.

$$y = -2.0219x + 434.32$$

Where y = arsenic concentration in μg/L, and x is the blue value reading of the colour from the picture taken of the strip after testing. Any value that is 0 or negative using this equation means no arsenic is present in the water.

These values can be seen in table 2.

Test number	Initial concentration of arsenic in water (μg/L)	Final concentration of arsenic in water using testing kit (μg/L)	Final concentration of arsenic in water using software (μg/L)
1	20	<5	1.45
2	40	<5	4.64
3	20	0	0

Table 2: Final arsenic concentration in water gotten from testing kit and software.

5. Discussion and recommendations

5.1 Discussion

The experiments carried out show that a composite of iron loaded biochar made from the post pyrolysis impregnation of Iron (III) nitrate nonahydrate to pine wood biochar is effective at removing arsenic from water using the cartridge-based filter design tested. The results could not be fully given as a value two of the tests when using the testing kit because of the nature of the testing kit used. The kit only reads whole number values if they are 0, 5, 10 µg/L and other numbers shown on the picture of the kit in Appendix 6. If any value is below 5 but above 0, a faint colour appears on the strip, but this colour cannot be read as a value because the kit doesn’t have colour matches for these values and seeing colours below a certain intensity with the naked eyes can be strenuous for the eyes. Therefore, a better testing kit is necessary to get an appropriate numbered value of the amount of arsenic found in the water after testing and using the software we made is a more effective way to get a more accurate testing value. The software will not only show correct results for colours on the strip, but it will also help get more accurate values for colours that do not fall on the range of colours with the kit. The experiments were limited by factors such as time, delays to receive products ordered and in turn, the unavailability of access to some materials needed for testing. This made the number of tests done small, and the scale very small, thus, the were not repeated to determine whether or not we get same results. The results for test 3 for example needed to be repeated before a conclusion can be made about the amount of adsorbent affecting the rate of filtration. From test 3, doubling the amount of adsorbent let to more arsenic removal, but further testing is needed to conclude on this. Some recommendations that could be done to get better results are discussed with access to all the resources needed are discussed in the section 5.2.

After testing the colour of the strips and running them through the colour identification process, the software was able to identify the concentration of <5 ppb as expected. The software method was also able to detect a specific concentration of arsenic between the intervals of 0 and 5 ppb. This is quite beneficial as before using the software it could only be indicated that the concentration was less than 5ppb or possible 0 as the shade differentiation was difficult to do by eye. A line of best fit using a polynomial method to the power of 3 was acquired for the graph created from the collected blue values on the colour identification card and the equation was extracted from that line of best fit. A second line of best fit was acquired using a linear method from the concentration of 0-50ppb as the equation using the polynomial equation was drastically skewed when testing the blue values close to the beginning or end of the trend line, giving unreasonable results when calculating concentrations near the end points, requiring narrowing the equation down to a smaller section of the graph near the end to get a more appropriate trend line of that section. The maximum limit in Bangladesh is 50ppb so that was the new limit set, as the rest of the graph seemed to only skew the equation more than necessary at the end. These graphs can be seen in the spreadsheet in Appendix 7. There may be some inaccuracies due to the changes that ImageJ can have dependent on the ROI selected when analyzing the colour, no two analysis are exactly the same depending on the ROI selected, though very similar numbers are typically given. This explains why there may be issues with creating a line of best fit that can accurately fit the scatter plot from beginning to end as these inaccuracies over the entire plot may create large discrepancies for the line of best fit.

5.2 Recommendations

5.2.1 Detection software

As mentioned before, the original plan for this detector was to be fully integrated into an app, but due to time, resources and some available skill sets this was not achievable. This method provides a basic framework for what can be integrated into an app in the future. Other features that should be added on, as mentioned in the original design of the app include a manual for both the filter and app, a calendar to remind the user to change the filter and other product information. It would also be ideal in this app that the taking of pictures and calibration be less manual and more automated by the app. The app would instruct what photos to take when and would automatically calibrate the best fit line, then match the photo of the test to the best fit line automatically after the picture is taken.

The original method this detector is based on uses a spectrometer in order to take pictures of the sample in one of their methods, this would be harder to do in the field quickly, so this was eliminated, but finding ways to improve the photo quality taken would be something to consider for future development. Since the tests were done in a more controlled environment than what may be available in actual field tests, this method should also be tested under perhaps more field realistic situations. This method was also tested only with one arsenic sampling kit, the method should be tested with other kits that use different colour ranges to ensure further compatibility with a variety of arsenic testing kits. There may also be more advanced software available or that could be independently coded to reduce error in colour identification based on the software's limitations.

Detection Kit:

The detection kit was not very precise, thus getting a more precise detection kit is important. If there was more time, a different kit which reads smaller more defined values and has a higher accuracy and precision in reading the values of the amount of arsenic found in the water would have been ordered. The flexibility of the detection software will also be beneficial with using such a kit because the excel file and equations are easily adjustable. Due to the time needed to get this kit and the process required with it, we decided to get the current kit and program the software with it.

5.2.2 Filter recommendations

Testing:

Another suggestion for testing using a cartridge is to run water through the cartridge for about 3 times before beginning testing. In the experiments, this was not done because there was not enough arsenic contaminated water present to do this and using clean water could have influenced the results of the test (arsenic contaminated water at known concentration can mix with clean water in cartridge thereby changing concentration of arsenic contaminated water). In a situation where there was enough arsenic solution, running some of it through the filter to make it compact will ensure that any lose media that finds its way through comes out in the first three runs, and by the fourth run no more media comes out. A test using pure water was done to determine that three runs is the average number of times to have the water pass through the cartridge, for there to be clear water without any media running out afterwards. This does not remove media that may have already accumulated in the polypropylene pads which are at the bottom of the cartridge already, and thus may not be the solution to having media stay on the pads.

More tests

If more arsenic solution was present, more tests could have been carried out to measure the repeatability, and the amount of tests/ time needed to replace the filter. Although this was not done a recommendation is that more testing is needed to get more accurate results and determine the values of replacement and repeatability.

6. Cost analysis

This project was funded by the Bioresource Engineering Student Society (BESS) and the team's supervisor, Professor Susan Gaskin. BESS was able to fund the team with $140 which covered the cost of materials while Professor Gaskin was able to provide the chemicals (ferric nitrate and arsenic solution) and lab equipment and space for the testing. All materials purchased by the team were done on Amazon.ca. The team personally purchased the testing kit, a 5-liter HDPE container with a spigot, biochar, cartridge and filter. The Ferric Nitrate was purchased from Fisher Scientific and the arsenic solution was prepared by a laboratory in the department of Earth science at McGill. A breakdown of all purchased and used materials can be seen in table 3, Appendix 8. The cost of the software for colour identification is zero dollars as ImageJ is a free opensource software and if Excel from word is not available Google Sheets or other spreadsheet software can be used (lack of internet in this case may be problematic depending on alternative software chosen).

7. Conclusion

Drinking water contamination by arsenic is a problem faced by many countries around the world. There are some detection and filtration techniques available to test and treat arsenic contaminated water, but there is need for an improved easy to use at home and a cheap reliable filtration method. Before (or after filtration), detection is (or may be) needed. Determining whether or not arsenic is present in water depends on the method of detection used. Effectively reading the results of the detection test can be an issue, thus there is a need for a more reliable detection results interpretation system. In this paper, we reviewed the existing techniques for detection and filtration, and came up with criteria to weigh these methods in order to determine which was efficient and easily usable for at home tests. Based on these criteria, the most efficient detection method for at home use; paper-based test and visual aid device, and the most promising method for filtration which could be modified and improved for better filtration; adsorption using an iron loaded biochar adsorbent were chosen. With this, a software was made to ease interpretation of the results from this detection method in order to get more accurate results with less human errors. A filter test was done using modified components of the adsorbent from those used in other literature reviewed in order to determine the efficiency of the adsorbent in removing arsenic. The filter showed a good efficiency of arsenic removal, but more tests are needed to further prove this. The detection software made is easy to use and was handy in interpreting results from our filter tests. In general, the methods for the detector software and filter are efficient, easy to operate, cost effective and environmentally sustainable. Overall, some tests were done, and the combined system (filter and detector software) was used in this study, but more testing and comparison of our results with other literature is needed to be able to get full well tested results.

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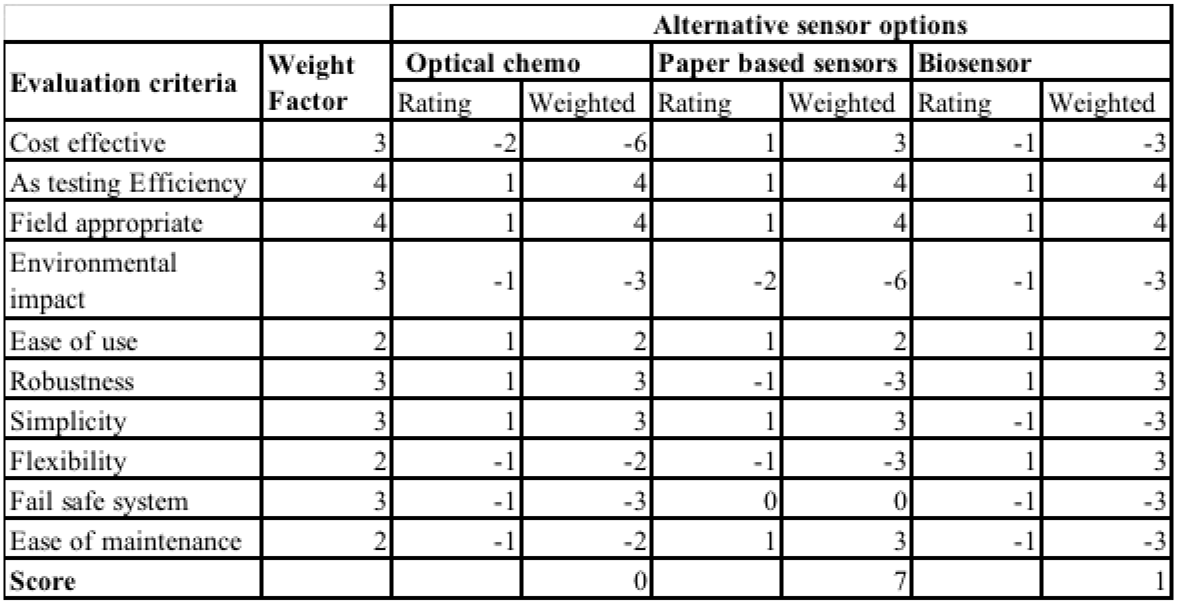
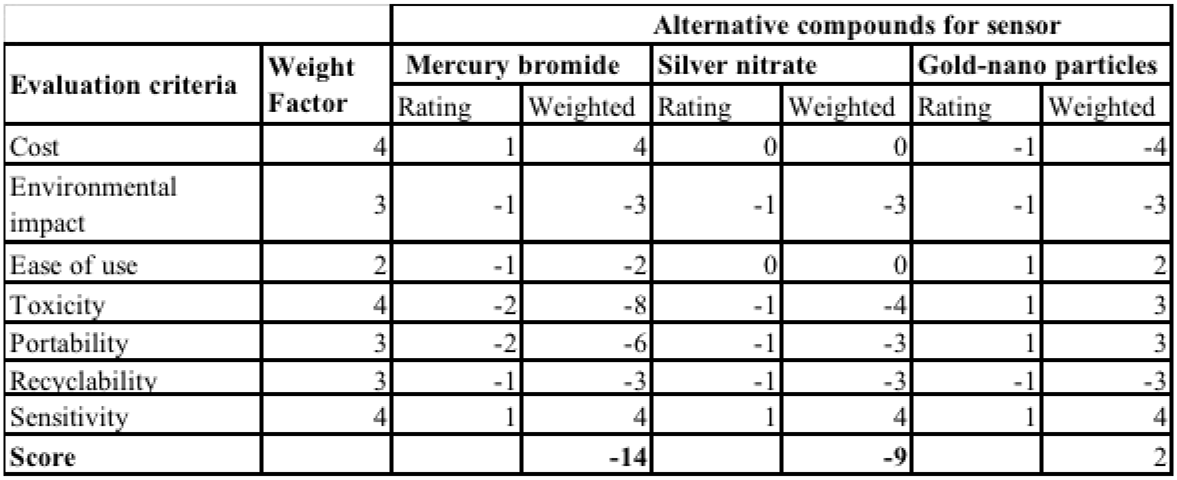
Appendix 1



		Alternative sensor options					
Evaluation criteria	**Weight Factor**	**Optical chemo**		**Paper based sensors**		**Biosensor**	
		Rating	Weighted	Rating	Weighted	Rating	Weighted
Cost effective	3	-2	-6	1	3	-1	-3
As testing Efficiency	4	1	4	1	4	1	4
Field appropriate	4	1	4	1	4	1	4
Environmental impact	3	-1	-3	-2	-6	-1	-3
Ease of use	2	1	2	1	2	1	2
Robustness	3	1	3	-1	-3	1	3
Simplicity	3	1	3	1	3	-1	-3
Flexibility	2	-1	-2	-1	-3	1	3
Fail safe system	3	-1	-3	0	0	-1	-3
Ease of maintenance	2	-1	-2	1	3	-1	-3
Score			0		7		1

Table 1: Pugh chart for sensors

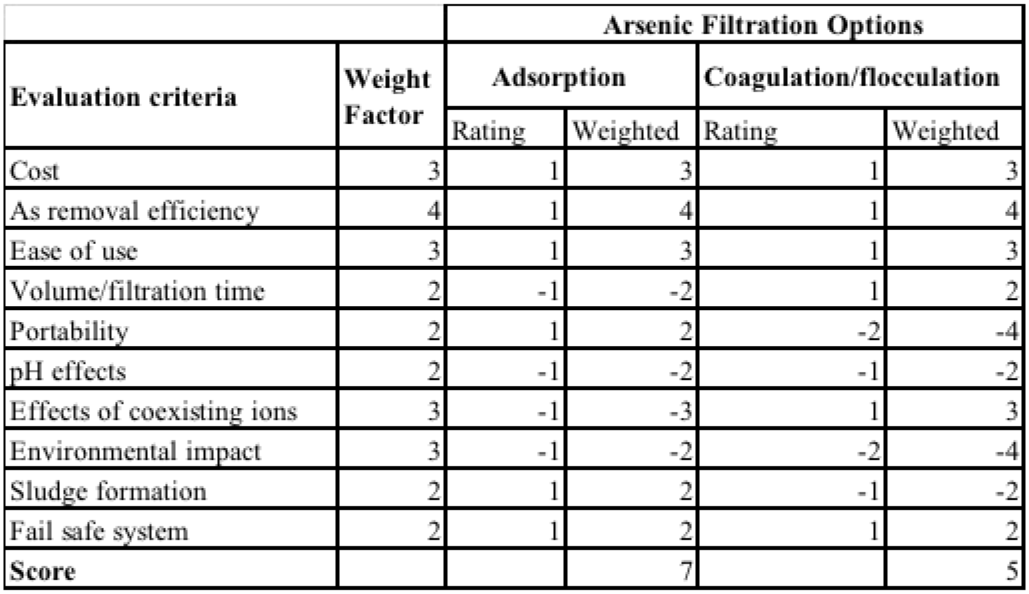
Appendix 2



		Alternative compounds for sensor					
Evaluation criteria	**Weight Factor**	**Mercury bromide**		**Silver nitrate**		**Gold-nano particles**	
		Rating	Weighted	Rating	Weighted	Rating	Weighted
Cost	4	1	4	0	0	-1	-4
Environmental impact	3	-1	-3	-1	-3	-1	-3
Ease of use	2	-1	-2	0	0	1	2
Toxicity	4	-2	-8	-1	-4	1	3
Portability	3	-2	-6	-1	-3	1	3
Recyclability	3	-1	-3	-1	-3	-1	-3
Sensitivity	4	1	4	1	4	1	4
Score			**-14**		**-9**		2

Table 2: Pugh chart for paper-based sensor chemicals.

Appendix 3



		Arsenic Filtration Options			
Evaluation criteria	**Weight Factor**	**Adsorption**		**Coagulation/flocculation**	
		Rating	Weighted	Rating	Weighted
Cost	3	1	3	1	3
As removal efficiency	4	1	4	1	4
Ease of use	3	1	3	1	3
Volume/filtration time	2	-1	-2	1	2
Portability	2	1	2	-2	-4
pH effects	2	-1	-2	-1	-2
Effects of coexisting ions	3	-1	-3	1	3
Environmental impact	3	-1	-2	-2	-4
Sludge formation	2	1	2	-1	-2
Fail safe system	2	1	2	1	2
Score			7		5

Table 4: Pugh chart of arsenic filtration methods.

Appendix 4

		Adsorbent options					
Evaluation criteria	**Weight Factor**	**Iron-oxyhydroxide**		**Biochar**		**Hybrid (iron-loaded biochar)**	
		Rating	Weighted	Rating	Weighted	Rating	Weighted
Cost effective	3	1	3	1	3	-1	-3
As removal Efficiency	4	1	4	-2	-8	1	4
Availability	3	-1	-3	1	3	1	3
Environmental impact	2	-2	-4	1	2	-1	-2
Ease of preparation	2	1	2	1	2	1	2
Score			2		3		4

Table 5: Pugh chart of adsorbents.

Appendix 5

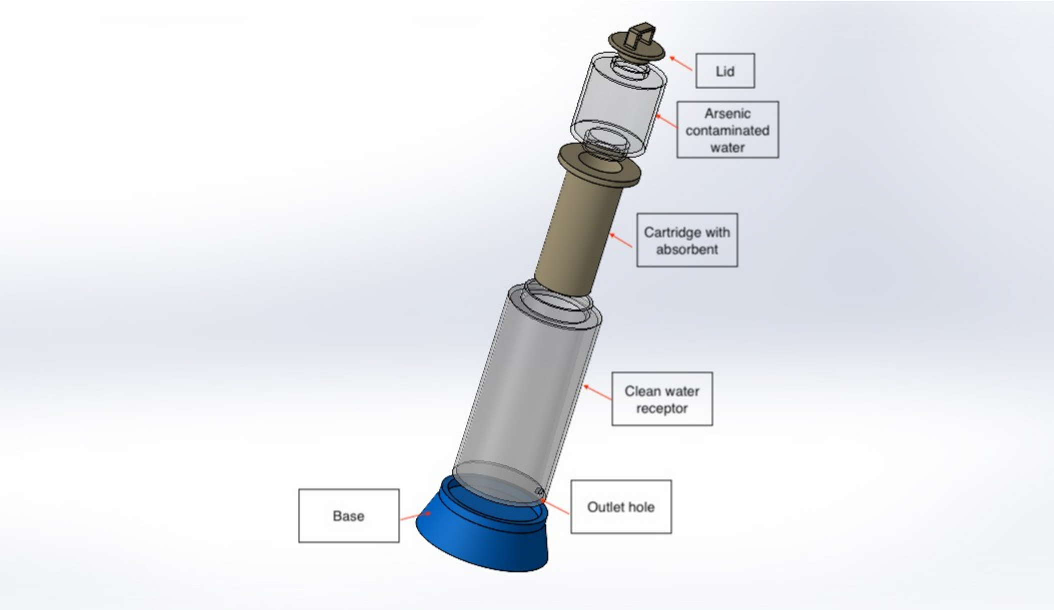
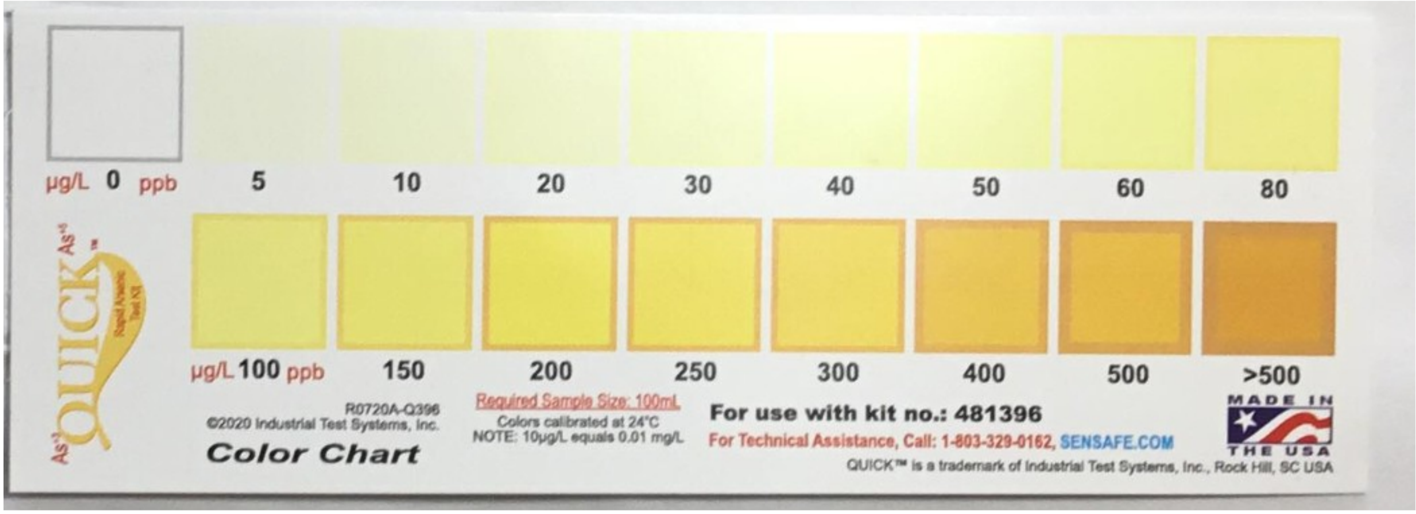


Fig 2: Image of prototype of filter.

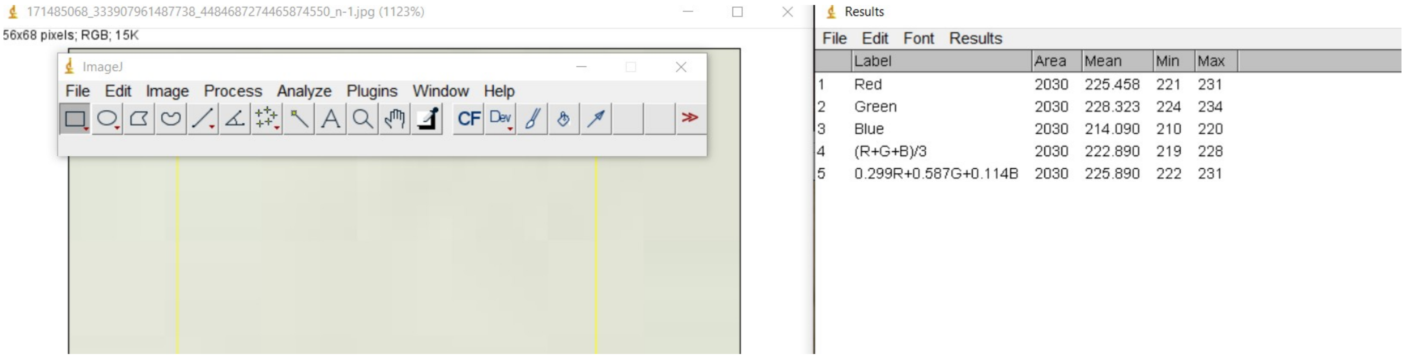
Appendix 6



Colour strip from testing kit

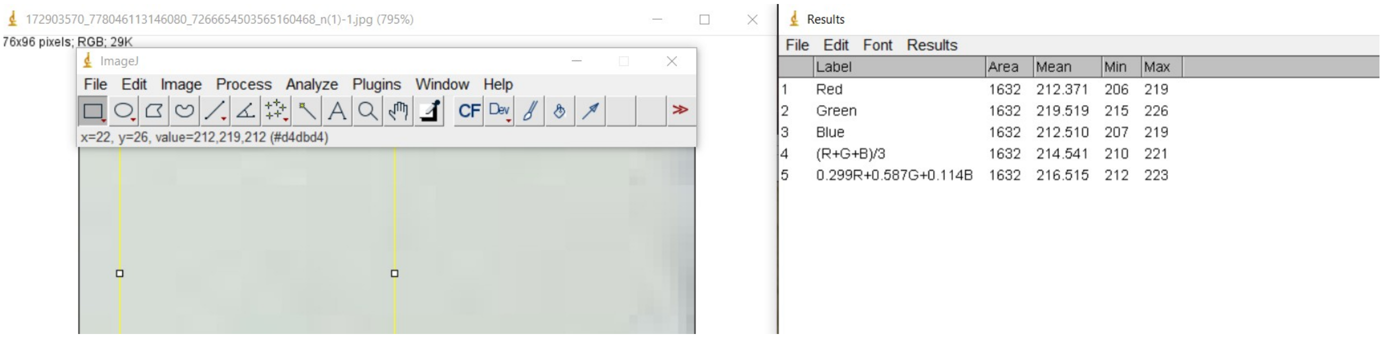
Appendix 7

Test 1



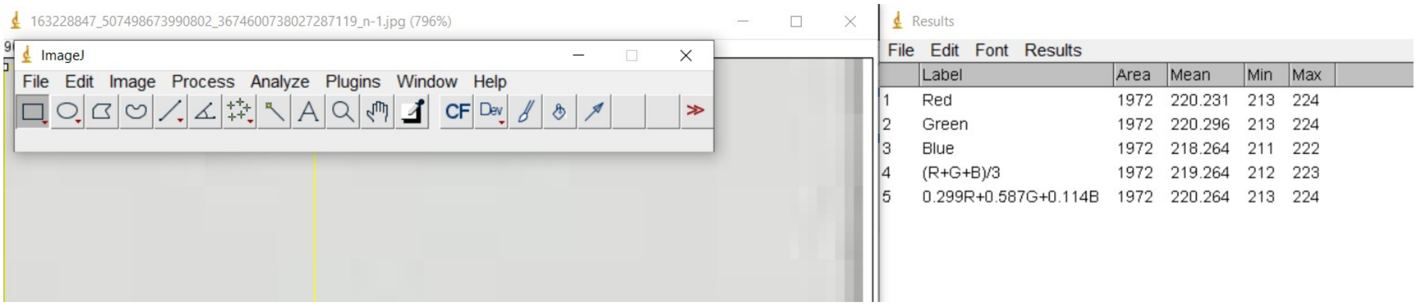
	Label	Area	Mean	Min	Max
1	Red	2030	225.458	221	231
2	Green	2030	228.323	224	234
3	Blue	2030	214.090	210	220
4	(R+G+B)/3	2030	222.890	219	228
5	0.299R+0.587G+0.114B	2030	225.890	222	231

Test 2



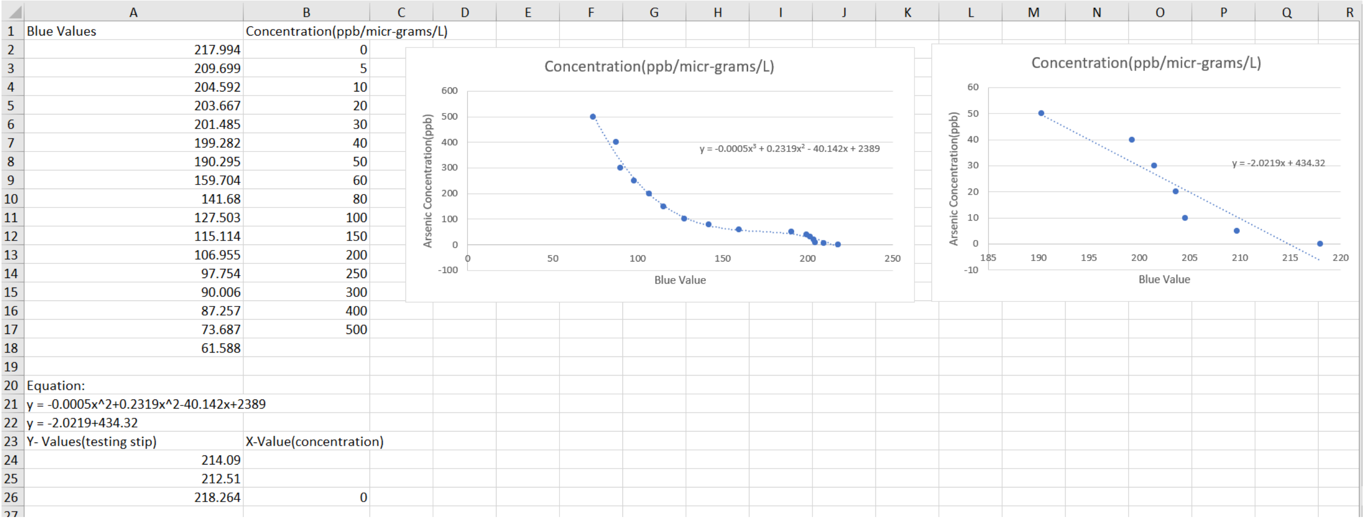
	Label	Area	Mean	Min	Max
1	Red	1632	212.371	206	219
2	Green	1632	219.519	215	226
3	Blue	1632	212.510	207	219
4	(R+G+B)/3	1632	214.541	210	221
5	0.299R+0.587G+0.114B	1632	216.515	212	223

Test 3



	Label	Area	Mean	Min	Max
1	Red	1972	220.231	213	224
2	Green	1972	220.296	213	224
3	Blue	1972	218.264	211	222
4	(R+G+B)/3	1972	219.264	212	223
5	0.299R+0.587G+0.114B	1972	220.264	213	224

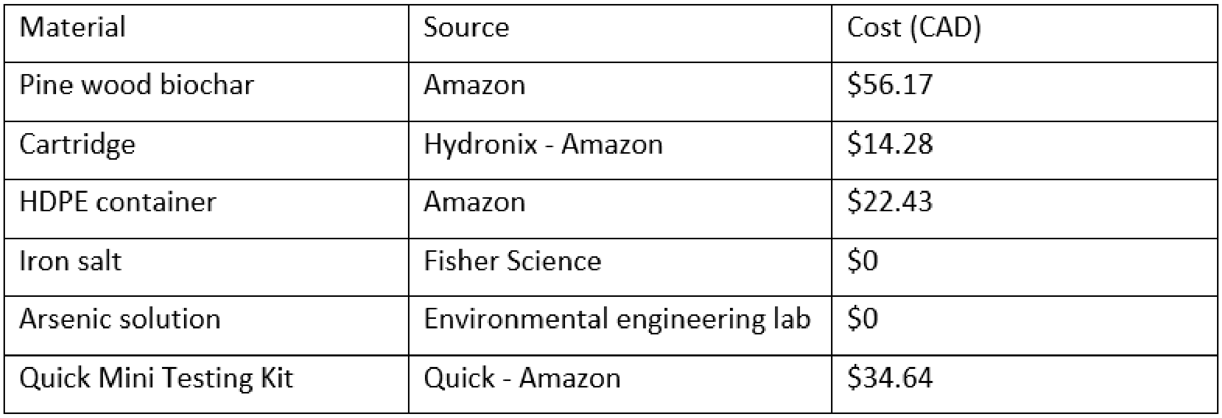
ImageJ results of RGB values of colours gotten from filter testing.



	A	B
1	Blue Values	Concentration(ppb/micr-grams/L)
2	217.994	0
3	209.699	5
4	204.592	10
5	203.667	20
6	201.485	30
7	199.282	40
8	190.295	50
9	159.704	60
10	141.68	80
11	127.503	100
12	115.114	150
13	106.955	200
14	97.754	250
15	90.006	300
16	87.257	400
17	73.687	500
18	61.588	
19		
20	Equation:	
21	y = -0.0005x^2+0.2319x^2-40.142x+2389	
22	y = -2.0219+434.32	
23	Y- Values(testing stip)	X-Value(concentration)
24	214.09	
25	212.51	
26	218.264	0

Excel sheet with linear and polynomial graph analysis of ImageJ results to get the value of arsenic concentration in the water sample.

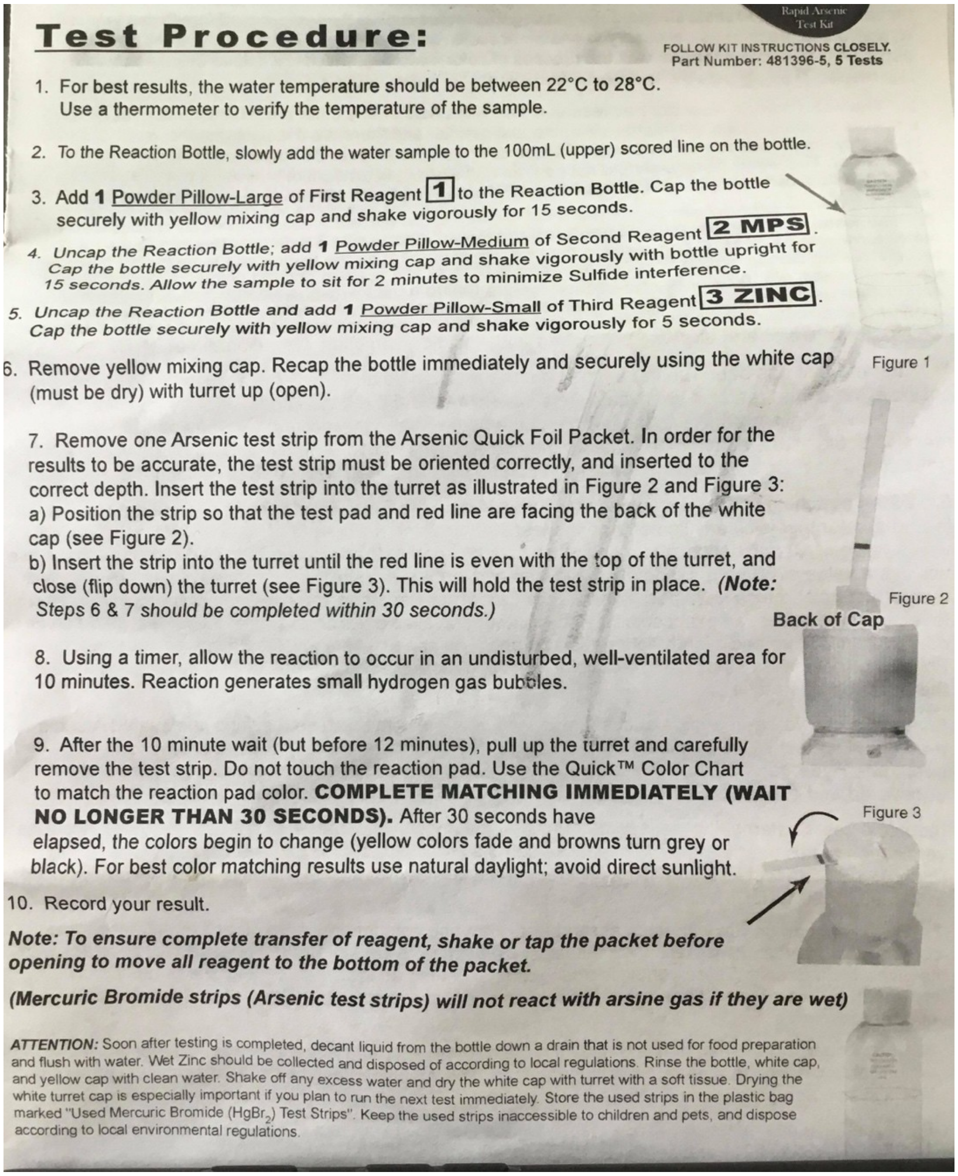
Appendix 8



Material	Source	Cost (CAD)
Pine wood biochar	Amazon	$56.17
Cartridge	Hydronix - Amazon	$14.28
HDPE container	Amazon	$22.43
Iron salt	Fisher Science	$0
Arsenic solution	Environmental engineering lab	$0
Quick Mini Testing Kit	Quick - Amazon	$34.64

Table 6: Cost breakdown for filter.

Appendix 9



Test Procedure:

FOLLOW KIT INSTRUCTIONS CLOSELY.
Part Number: 481396-5, **5 Tests**

1. For **best** results, the water **temperature** should be between **22°C to 28°C**. Use a thermometer to verify the temperature of the sample.
2. To the Reaction Bottle, slowly add the water sample to the 100mL (upper) scored line on the bottle.
3. Add **1** Powder Pillow-Large of **First Reagent** **1** to the **Reaction Bottle**. Cap the bottle securely with yellow mixing cap and shake vigorously for 15 seconds.
4. *Uncap the Reaction Bottle; add **1** Powder Pillow-Medium of Second Reagent* **2 MPS**. *Cap the bottle securely with yellow mixing cap and shake vigorously with bottle upright for 15 seconds. Allow the sample to sit for 2 minutes to minimize Sulfide interference.*
5. *Uncap the Reaction **Bottle** and add **1** Powder Pillow-Small of Third Reagent* **3 ZINC**. *Cap the bottle securely **with yellow** mixing cap **and shake** vigorously for 5 seconds.*
6. Remove yellow mixing cap. Recap the bottle immediately and securely using the white cap (must be dry) with turret up (open).
7. Remove one Arsenic test strip from the Arsenic Quick Foil Packet. In order for the results to be accurate, the test strip must be oriented correctly, and inserted to the correct depth. Insert the test strip into the turret as illustrated in Figure 2 and Figure 3:
   a) Position the strip so that the test pad and red line are facing the back of the white cap (see Figure 2).
   b) Insert the strip into the turret until the red line is even with the top of the turret, and close (flip down) the turret (see Figure 3). This will hold the test strip in place. ***(Note:** Steps 6 & 7 should be completed within 30 seconds.)*
8. Using a timer, allow the reaction to occur in an undisturbed, well-ventilated area for 10 minutes. Reaction generates small hydrogen gas bubbles.
9. After the 10 minute wait (but before 12 minutes), pull up the turret and carefully remove the test strip. Do not touch the reaction pad. Use the Quick™ Color Chart to match the reaction pad color. **COMPLETE MATCHING IMMEDIATELY (WAIT NO LONGER THAN 30 SECONDS).** After 30 seconds have elapsed, the colors begin to change (yellow colors fade and browns turn grey or black). For best color matching results use natural daylight; avoid direct sunlight.
10. Record your result.

Note: To ensure complete transfer of reagent, shake or tap the packet before opening to move all reagent to the bottom of the packet.

(Mercuric Bromide strips (Arsenic test strips) will not react with arsine gas if they are wet)

ATTENTION: Soon after testing is completed, decant liquid from the bottle down a drain that is not used for food preparation and flush with water. Wet Zinc should be collected and disposed of according to local regulations. Rinse the bottle, white cap, and yellow cap with clean water. Shake off any excess water and dry the white cap with turret with a soft tissue. Drying the white turret cap is especially important if you plan to run the next test immediately. Store the used strips in the plastic bag marked "Used Mercuric Bromide ($HgBr_2$) Test Strips". Keep the used strips inaccessible to children and pets, and dispose according to local environmental regulations.

Procedure from testing kit for arsenic detection.

Appendix 10

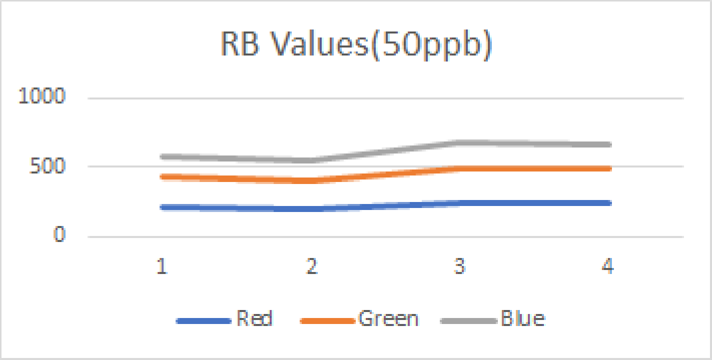


Fig 3. RGB sensitivity test over multiple lighting environments for a concentration of 50 ppb.

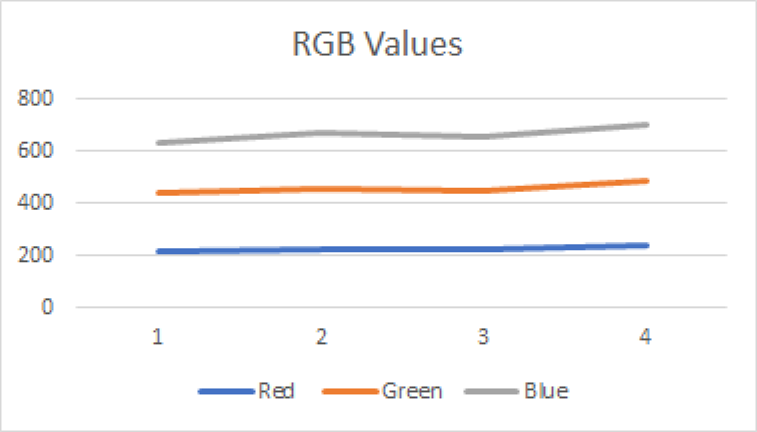


Fig 4. RGB sensitivity test over multiple lighting environments for a concentration of 5 ppb.