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At a well in the village of Hounde, 250 km south-west of Ouagadougou. Photo by Katti Ewald

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Abstract

Ferrihydrite in a suspension have been studied as a solution for purification of arsenic contaminated water. Many development countries, amongst them Burkina Faso, have arsenic in their groundwater and the current methods for purification are too expensive. Measurements have shown extreme values of arsenic in the groundwater in several places in Burkina Faso. Since the availability of surface water is limited, the groundwater is still used as drinking water.

Ferrihydrite has capacity to adsorb arsenic suspended in water due to its chemical characteristics. Small-scale laboratory work with ferrihydrite solutions have been performed in Ouagadougou, Burkina Faso. To purify the water with regard to the economical and practical circumstances in Burkina Faso, a column with safety filter was made out of simple materials such as plastic bottles, plastic tubes and glass wool. The contaminated water was flowing upwards through the column to prevent the filter from clogging.

This project has been performed in collaboration with a group of three students in Uppsala, Sweden. Similar experiments were performed at the same time and the results from Uppsala were implemented on the laboratory work in Burkina Faso. In Uppsala it was discovered that a 1 L ferrihydrite suspension containing 10 g ferrihydrite can adsorb 0.7 g arsenic while it was shaken and centrifuged well. In Burkina Faso it was possible, in the setup, to clean 2 L arsenic contaminated water with the concentration of 100 µg/L. The conclusions from the experiments in this project are that ferrihydrite can adsorb arsenic in contaminated water but that the setup used needs to be further evaluated.

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1 Introduction

Here follows an introduction to the areas of interest for this report. The introduction includes information of the situation in Burkina Faso and also gives an insight in the project's starting point.

1.1 Background

Clean water is essential for all human beings and still a lot of people on our planet lack access to clean and safe drinking water. In many parts of the world the drinking water is contaminated, which may cause serious health problems. Arsenic in the groundwater is a large-scale problem in areas such as West Africa and South East Asia. There are developed techniques for removing arsenic so that the water has an arsenic level below the recommended limit. These techniques are expensive to apply in many countries and therefore not realistic as solution in many developing countries (WHO, 2008).

The problem in Burkina Faso is mainly naturally caused by the content of arsenic in the bedrock, primarily Birimian volcano sedimentary and plutonic rocks (Smedley, Maiga & Knudsen, 2007). Burkina Faso is located in West Africa and is covered by three climate zones, where the northern parts are drier than the southern parts (The World Bank, 2009). The lack of water for drinking, agriculture and husbandry is significant during long periods of the year. Surface water is limited and often contaminated with microorganisms, therefore groundwater is main source for drinking water. People living in these areas often have no other option but to use the ground water contaminated with arsenic (Savagado, 2006).

The World Health Organization (WHO) recommends the human intake of arsenic through water to be maximum 10 µg/L (WHO, 2008). According to a study in the northeast areas of Burkina Faso, the groundwater is enriched with arsenic in a range from < 0.5 µg/L up to extreme values such as 1630 µg/L. In these areas the dissolved arsenic is mostly in the form of arsenate, As(V). Calculations have shown that the median of the concentration of arsenic for the affected area is 15.1 µg/L, which is above the WHO guidelines (Smedley, Maiga & Knudsen, 2007).

1.2 Health situation in Burkina Faso due to arsenic exposure

Large doses of arsenic are toxic. However, being exposed to smaller doses of arsenic in the drinking water over a long term is causally related to increased risks of different kinds of cancer, for example in the skin, bladder, lungs or kidney. Also skin changes, such as hyperkeratosis and pigmentation changes are shown to be related to the arsenic concentration in drinking water. These health problems have been shown to occur after being exposed to concentrations equal to 50 µg/L or even less. There are theories that exposure of arsenic can cause other health effects, like diabetes and other kinds of cancer than those mentioned above, but the causality is not as clear (IPCS, 2001). Also problems in respiratory system, cardiovascular system and reproductive system may be related to a constant exposure of arsenic (Rahman et al., 2009).

A study from 2012 showed that approximately 30 % of the population in the northern part of Burkina Faso suffers from melanosis and approximately 46 % from keratosis (Somé et al., 2012). Most of the people with skin lesions, approximately 90 %, were older than 18 years old. Among children under 6 years old skin lesions were very rare which indicates the fact that the lesions appear after 5-15 years of exposure of arsenic (Agusa et al., 2009).

1.3 Previous studies within topic

Previous studies have been made about the water quality in the wells in the northern part of Burkina Faso. In 1979 a Dutch Consultancy agency (IWACO) made analyses of arsenic content in three boreholes, 80 km north of Ouagadougou, after receiving reports about health issues in that area. They found high contents of arsenic and the outcome was to close down the wells and the village was moved (Smedley, Maiga& Knudsen 2007).

Research about the groundwater quality and geology were made in the beginning of the 21st century. Vegetables and 31 tube wells in the province Yatenga, northern Burkina Faso, were analysed. It was found that more than 50 % of the water samplings contained more arsenic than 10 µg/L. The analysed vegetables were not contaminated by arsenic (Somé et al., 2012).

Studies at the Department of Chemistry, Swedish University of Agricultural Sciences (SLU), have shown that water can be purified from arsenic if pumped through a column with Granular Ferric Hydroxide (GFH®) (Mähler&Persson, 2013). GFH® is a commercial material for cleaning

drinking water from metal and arsenic contaminations. The material is efficient and can adsorb both arsenite and arsenate at short contact times (seconds). GFH® is said to be a low crystalline, mesoporousakaganeite and is produced by GEH Wasserchemie GmbH & Co (Mähler&Persson, 2013).

A study of how well GFH® works as an arsenic adsorbent and how a setup could be constructed was done in Burkina Faso in 2013 (Mähler&Persson, 2013). According to the results GFH® can adsorb arsenic well and its structure does not change even though a lot of water is pumped through it. It was also discovered that the contact time for the water in GFH® matters for the possibility of arsenic to be adsorbed. The longer time the water was in contact with the adsorbent the more arsenic could be adsorbed. In a column setup the length of the adsorbent should be five times the diameter of the column. For the GFH® to work in optimal way it should not be dried out and air bubbles in the system should be avoided (Mähler&Persson, 2013).

During a Minor Field Study in 2013 two students from Master Program in Environmental and Water Engineering at Uppsala University tested GFH® with a successful result, involving real arsenic contaminated water from Yatenga province in Burkina Faso. It was also noted that GFH® has the ability to self-regenerate (Lundin & Öckerman, 2013). Half a year later, two other students from the same program also went to University of Ouagadougou in Burkina Faso for further studies. They discovered that the GFH® had the adsorption capacity of maximum $370 \mu\text{g}$ arsenic/cm³ adsorbent (Frid & Haglind, 2014). Since GFH® is a commercial product it is therefore expensive and not ideal for a country like Burkina Faso.

1.4 Aim

The aim of this study was to evaluate the capacity of using a cheap material for purification of arsenic contaminated groundwater in Burkina Faso. The material was ferrihydrite, an iron oxy-hydroxide. During this project, experiments were made in Ouagadougou, Burkina Faso. At the same time, experiments were performed in Uppsala, Sweden, and the results were exchanged between the two groups.

When studies about cleaning arsenic in Burkina Faso started it was a cooperation between SLU in Uppsala and University of Ouagadougou in Burkina Faso. Ferrihydrite has earlier been tried and discovered as a good arsenic adsorbent but there were problems with clogging in the setup. In this

study a setup with a flow from the bottom of the column going upwards was therefor evaluated, with the expectation to avoid clogging.

To concretise the aim of this study, the work was based on following questions:

In which extension can ferrihydrite adsorb arsenic from contaminated water with simple methods and at a low cost?

How well is a setup, where water is lead upward through a column containing a suspension of ferrihydrite, working for cleaning of water contaminated with arsenic?

Can glas wool be used as protection filter to prevent leakage offerrihydrite to the outgoing water in such a setup? How will this filter be arranged in the setup?

2 Theory

This part works through the fundamental information needed to understand the processes and results in this project.

2.1 Arsenic

Arsenic is found in groundwater in the forms of arsenate or arsenite, which has the oxidation state of +V respectively +III (Smedley, Maiga & Knudsen, 2007). Normally, As(III) is more common in deoxygenated waters, while As(V) is often found in waters with a better oxygen supply. Both these forms of arsenic will rapidly be absorbed from the gastrointestinal tract (WHO, 2008). The appearance of arsenic in groundwater is mainly caused by dissolution of rocks, minerals and ores, but industrial effluents and atmospheric deposition also contribute to the spreading of arsenic in water (WHO, 2011).

2.2 Ferrihydrite

Ferrihydrite is an iron oxy-hydroxide often used for cleaning drinking water from contaminations, as for example arsenic (Jambor&Dutrizac, 1998). Its approximate formula is $\text{Fe}_5\text{HO}_8 \cdot 4\text{H}_2\text{O}$ and it has a structure that is less well defined than other iron oxy-hydroxides, such as goethite, lepidocrocite and akaganeite (Mähler&Persson, 2013). It has a high adsorptive

capacity, a large surface area and a relatively poor crystallinity, which are three properties that can be important for removal of contaminations in drinking water. Ferrihydrite can also be produced at low costs, which makes it attractive under simple conditions (Jambor&Dutrizac, 1998).

An iron oxy-hydroxide surface has a positive or negative charge depending on pH. At high pH the iron oxy-hydroxide is negatively charged and at low pH the surface is positively charged (Eriksson et al., 2011). The pH, where the positive and negative charges at the surface balance each other, is called point of zero charge (pH_{PZC}). The types of ions that can adsorb to the surface depend partly on the charge of the iron oxy-hydroxide. Ferrihydrite has a pH_{PZC} of around 8.1 (Mähler&Persson, 2013).

A ferrihydrite suspension can be used to remove arsenic from drinking water. The iron oxy-hydroxide can adsorb arsenic in two of its ion forms; arsenite and arsenate. Earlier studies have shown that the arsenate adsorption is greater at lower pH whereas arsenite is more adsorbed to ferrihydrite at higher pH. Some earlier experiments have also shown that the adsorption of arsenate and arsenous acid can be effective even at short (minutes) contact times (Raven, Jain & Loepert, 1998). The relatively high pH_{PZC} makes ferrihydrite a good adsorbent of arsenic contaminations in drinking water, but the small size of the particles in a suspension can cause problems. The filter between the column and outlet was clogged. The problem was that the ferrihydrite sedimented by the gravity and became too thick for water to pass through (Mähler&Persson, 2013).

In nature ferrihydrite occur in sediments and soils with alternate redox conditions (Wu et al., 2015). However, ferrihydrite can also be prepared in artificial ways where sodium hydroxide solution and iron(III) nitrate solution is added to water during stirring and after a while a deposit, ferrihydrite, is formed (Wu et al., 2015).

Iron in drinking water is normally not a problem, since iron is an essential nutrient for humans (Minnesota Department of Health, 2015). However, high doses of iron intake can cause iron poisoning, the lethal dose is about 200–250 mg/kg of body weight (WHO, 2003). Ferrihydrite is a deposit and not so easily absorbed by the cells, since it first must be dissolved to be able to be absorbed (Albertsen, 2006).

3 Collaboration with Uppsala

The work in Burkina Faso at the University of Ouagadougou has been performed in collaboration with a group working at the Swedish University of Agricultural Science in Uppsala. Small-scale laboratory work with ferrihydrite solutions has been performed and results have been exchanged between the two groups.

3.1 Experiments in Uppsala

In Uppsala they noticed that the ferrihydrite was containing small particles which were difficult to keep from following the water through the filter made of glass wool. To remove the smallest particles from the ferrihydrite, the suspension was washed. After adding regular tap water, the ferrihydrite was shaken and put to rest. Due to the fact that ferrihydrite is denser than water, the ferrihydrite particles sank to the bottom of the bottle. When sedimentation had occurred, the top layer containing water and small particles could be poured out, leaving only the bigger particles. The procedure was repeated 5-6 times. Thanks to the washing the sedimentation time of the ferrihydrite in the column was reduced.

The first prototypes of the setup in Uppsala had only one filter made of glass wool. The construction of the column and the filter of glass wool were developed with previous MFS studies in mind. Due to several problems with leakage of ferrihydrite in the outflow, a new design with two filters was developed and worked successfully.

A adsorption experiment was done in Uppsala to test the ability of the ferrihydrite suspension to adsorb arsenic. A solution with 10 g ferrihydrite was produced, using the method in Appendix 1, but scaling up to $48 \text{ g Fe}_5\text{HO}_8 \cdot 4\text{H}_2\text{O}$ instead. The solution was then diluted with regular tap water to reach the total volume of 1 L. A known amount of As(V) was added to the solution and the bottle was shaken to guarantee a good mix. Samples from the solution were poured into two sampling tubes á 45 mL and placed in a centrifuge. The samples were centrifuged for 15 minutes, until the iron particles had sediment in the bottom of the tubes. Finally, the arsenic absorbance was measured with an atomic absorption spectrometer. Different amount of arsenic was added and the procedure was repeated until the atomic adsorption spectrometer detected arsenic in the

samples. Two calibration solutions were made to be able to do a calibration curve and to calculate the amount arsenic adsorbed by the ferrihydrite. Result in Appendix 3

3.2 Results Uppsala

The methods tested and developed in Uppsala could be successfully implemented in Ouagadougou. Thanks to the double filter of glass wool and the washing of ferrihydrite, no ferrihydrite was seen in the outgoing water. The batch experiment showed that 0.500 g As(V) could be added to a 1 L ferrihydrite suspension containing 10 g ferrihydrite with all As(V) adsorbed. When 0.800 g arsenic was added to the batch test, arsenic was detected in the clear, overlaying solution after centrifugation. The conclusion is that 1 L of ferrihydrite suspension containing 10 g ferrihydrite can adsorb arsenic in a concentration of around 0.7 g, with a contact time of about 0.5 h.

4 Method

The method explains the practical work leading to the result of the project.

4.1 Setup

4 plastic bottles á 0.5 L
Tubes
Electrical tape
Silicon
Parafilm
Tanks
Electrical pump
Glass wool
Ferrihydrite
1.5 L plastic bottle
Multitool
Sandpaper
Chemistry stand



Figure 1: Setup made out of tubes and plastic bottles. An electrical pump was used to create a stable flow.

The setup was made out of tubes and bottles, sealed with silicon and plastic tape, see Figure 1. To create a stable flow an electrical pump were used. The column was built out of four 0.5 L bottles. For the bottom part of the column a bottle with a straight shape was chosen. The nether part of the bottle was removed close to the bottom. The bottle was put upside down with the cut opening upwards. For the top of the column three bottles with more rounded shapes were used. One was cut on the middle and placed on the bottom bottle. The two bottles fitted well together and parafilm and electrical tape were used to seal the small gap between them. After that, the two other top bottles were cut closer to the top and placed above the top bottle, to create a triple top. The edges were made soft using sandpaper. Glass wool was placed between the first and the second top and also between the second and the third top to create a double filter, see Figure 2. The top was sealed in the same way as the rest of the column, using parafilm and electrical tape. The column was altogether 36 cm high.

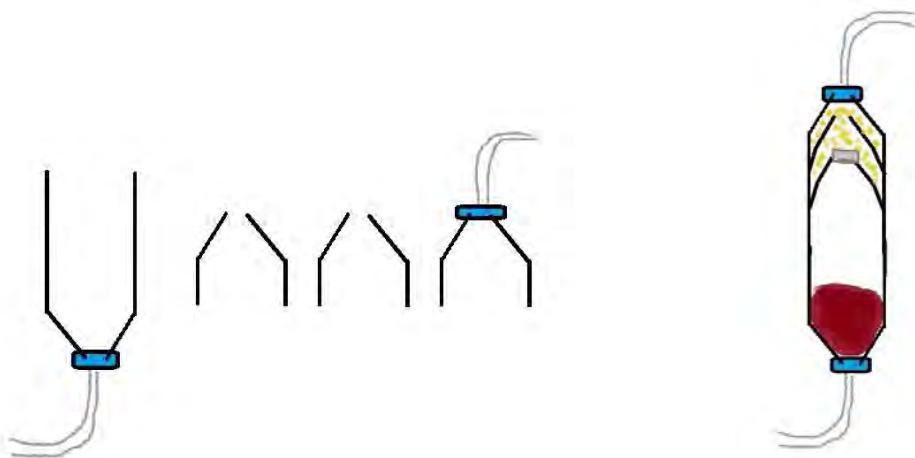


Figure 2: The four cut pieces of bottles, as shown above to the left, were put together as in the picture to the right. The glass wool was placed between the bottle necks in the top. The yellow color between the tops represents glass wool and the red color represents the ferrihydrite. .

Through the rest of the construction transparent silicon and electrical tape were used to seal all tubes together. The silicon dried for approximately twelve hours before being covered with electrical tape. To create a stable flow an IWAKI Electromagnetic Metering Pump (model EWN-B21VCER) was used in the inlet. The electrical pump made it possible to control and easily regulate the flowrate.

4.2 Ferrihydrite suspension

The ferrihydrite suspension was produced by adding 29 g $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ to 500 mL deionized water. This solution was well shaken and the pH was then changed to over 8 by adding 4 M NaOH. The next day, the pH was changed to 4.6 by adding 1 M HCl. The bottle was shaken before each pH measurement. The amount of 29 g $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ generated a solution with 6 g ferrihydrite. For a detailed description of the synthesis, see Appendix 1.

For the suspension used in the experiments with the setup, the smallest particles of the ferrihydrite suspension were removed by washing the ferrihydrite. This was done by shaking ferrihydrite with deionized water, letting the ferrihydrite sediment and then removing the overlaying clear fluid. See the sedimentation in Figure 3. This procedure was repeated five to six times and resulted in a ferrihydrite suspension without the smallest particles. For a detailed description of this process, see Appendix 2.



Figure 3: A sedimented ferrihydrite suspension.
The clear fluid can be seen on the upper layer.

4.3 Collection and preparation of water

During the second week in Ouagadougou 400 L of water was collected from two different wells in Hounde, a village 250 km south-west of Ouagadougou. In previous studies (Lundin & Öckerman, 2013; Frid & Haglind, 2014) water was collected from the Yatenga province. Due to

the security situation in Yatenga at the time of this project, it was too insecure to collect water there. The new place was chosen considering information from National Office of Water and Sanitation (Office National de l'Eau et de l'Assainissement –ONEA-), which indicated high amounts of arsenic in the Hounde area.

The result of total concentration of arsenic in well 1 was 14 µg/L and in well 2 there was no arsenic detected. The concentrations of arsenic in the two wells were lower than expected. The wells in the Yatenga province can have much higher concentrations, up to 1630 µg/L. To simulate the water of Yatenga, water from well 2 was contaminated to an arsenic concentration of 100 µg/L. Using water from these wells was still considered as a good option since the water was expected to have similar properties as the groundwater in Yatenga province considering other ions. This could be of importance since other ions might be competitive with arsenic in the adsorption.

To contaminate the water As(III) was used. First a powder of an arsenic salt was dissolved in 1 L deionized water, making a concentration of 1000 ppb. These solutions were then used to get different concentrations in the collected water. The concentrations of arsenic in the water were calculated from Equation 2.

$$c_1 V_1 = c_2 V_2 \quad (1)$$

Where c_1 and V_1 is the concentration and volume from the 1 L solution and c_2 and V_2 is desired concentration and volume of the water from the wells.

4.4 Running of the experiment

When the setup was ready the ferrihydrite suspension was poured into the inlet of the setup. Water from a 20 L tank with arsenic contaminated water was pumped into the setup with an electrical pump. The pump created a fairly steady flow. As soon as the water started to drip out of the outlet it was collected in volumetric flasks and poured into plastic bottles or plastic bags. The volume of water going through the setup and the time were noted.

4.4.1 Experiment 1

In this experiment the setup contained not contaminated water at the start. The ferrihydrite suspensions was poured in and the flow was stopped for 15 minutes allowing the ferrihydrite to sediment in the column in order to stay close to the bottom of the column. Water was collected in 1.5 L bottles and taken to a laboratory for analysis. The setup was estimated to contain a bit more than 1 L of water and was filled with water containing no arsenic at the start of the experiment. To have results only from the water contaminated with arsenic the first 1.5 L was not analysed. In the column it was approximately 3 g ferrihydrite and the average flow was 1.3 L/h.

4.4.2 Experiment 2

In this experiment the ferrihydrite suspension was first added to the empty column and then arsenic contaminated water was pumped in. When the plastic column was almost full the setup was left to rest, 15 minutes, to let the ferrihydrite sediment. Every 0.1 L was collected in a bottle or plastic bags to be analysed separately. Between every 2 L the setup was left to rest overnight. The column contained 6 g ferrihydrite and the average flow during the experiment was 0.5 L/h.

4.4.3 Experiment 3

In Experiment 3, same flowrate as in Experiment 2 was used, but now 5 L of water was let to pass through the column without any break. A new tank with 20 L of water from well 2 was contaminated and the initial concentration of arsenic was measured to 100 µg/L.

4.4.4 Experiment 4

Adsorption test was done almost in the same way as in Uppsala to test the ability of the ferrihydrite to adsorb arsenic. 0.25 L of a arsenic solution with a concentration of 1 g/L was added to a washed ferrihydrite suspension. The suspension contained 6 g ferrihydrite. The rest of the bottle was field up to 1 L with water from well 2. This gave approximately the same proportion as the adsorption test in Uppsala when the concentration of arsenic was 0.5 g/L and 10 g ferrihydrite was used. Samples from the solution were poured into 4 sampling tubes á 45 mL and placed in a centrifuge. The samples were centrifuged for 15 minutes, until the iron particles had sediment in the bottom of the tubes. The water over the sedimentation was sent to the lab for analyse. The experiment was done two times.

After analyses from the two tests it was decided to centrifuge the solutions again to see if a better sedimentation could be achieved. Two new tubes from each test were centrifuged for 30 minutes.

4.5 Method to analyse arsenic

The analyses were made at a laboratory outside the University, Laboratoire National d'Analyse des eaux (LNAE). For analysis of arsenic a Wagtech Arsenator was used. The instrument measured total concentration of arsenic in the water samples in the range of 1 – 500 µg/L (Wagtech Projects, 2016).

For measuring the total amount of arsenic in the water sulphamic acid powder was added to the water sample in order to make the arsenic distribute as free ions. In the next step sodium borohydrite was added and if arsenic was present in the solution, arsine gas with the same concentration of arsenic as the solution was formed. The gas raised and reached a filter of hydrogensulfide. According to the concentration of arsenic in the gas, the filter turned into a certain color and the concentration could be determined by a spectrophotometer. In total the analysis took 20 minutes (Rodier, 2009).

The water from well 2 was also further examined to determine its characteristics and its suitability to be used in the experiments. The amount of phosphate, nitrate, calcium, magnesium, iron as well as conductivity was analysed.

5 Results

Table 1 shows the results from analyses of ions in the water that was used in Experiment 1 and Experiment 2. The right column shows results from analyses made at water from the Yatenga province in 2014. These analyses were made in previous studies (Frid & Haglind, 2014) and are added here to give an idea of the suitability of the water used in this study.

Table 1: Analysis of ions in water from well 2 and water from Yatenga

Ion	Water from well 2	Water from Yatenga
Phosphate [mg/L]	0.87	0.35
Nitrate [mg/L]	3.1	7.1
Calcium [mg/L]	15.55	32
Iron [mg/L]	<0.02	0.01
Conductivity [μ S/cm]	704	345

The outgoing water from Experiment 2 was analysed regarding iron and phosphate. Iron was analysed after 8.0 L to examine if any iron from the ferrihydrite had followed the purified water. Phosphate was analysed after 2.2 L in order to see if phosphate concurs with arsenic in the ferrihydrite adsorption. The concentration was compared with the initial concentration. Results are shown in Table 2 bellow.

Table 2: Concentration in outgoing water and initial concentration of phosphate and iron from Experiment 2

Ion	Water passed through column [L]	Concentration [mg/L]	Initial concentration [mg/L]
Phosphate	2.2	0.47	0.87
Iron	8.0	0.07	<0.02

5.1 Experiment 1

In this experiment, clear water with no detection of orange color came out from the setup. The first glass wool was orange but the second was still white after the experiment. Table 3 shows the arsenic concentrations in Experiment 1.

Table 3: Arsenic concentration on outgoing water after different volumes had passed through the column. During the experiment an average flow of 1.3 L/h was used. The initial concentration was 100 µg/L

Volume water [L]	Arsenic concentration [$\mu\text{g}/\text{L}$]
0	100
3	13
4.5	73
9	100
10.5	100

5.2 Experiment 2

The last glass wool filter was still completely white after the experiment and the water coming out was clear. However, results from analyses demonstrated in Table 2 above showed that a small amount of ferrihydrite had leaked out with the outgoing water. Figure 4 shows the arsenic concentrations in Experiment 2. The experiment was paused after every 2 L during one night. The blue line represents the concentration in the outgoing water. Every blue dot represents a measured value. The red dot represents the initial concentration in the water and the green line the guideline value of daily intake made by WHO. For exact values see Appendix 5.

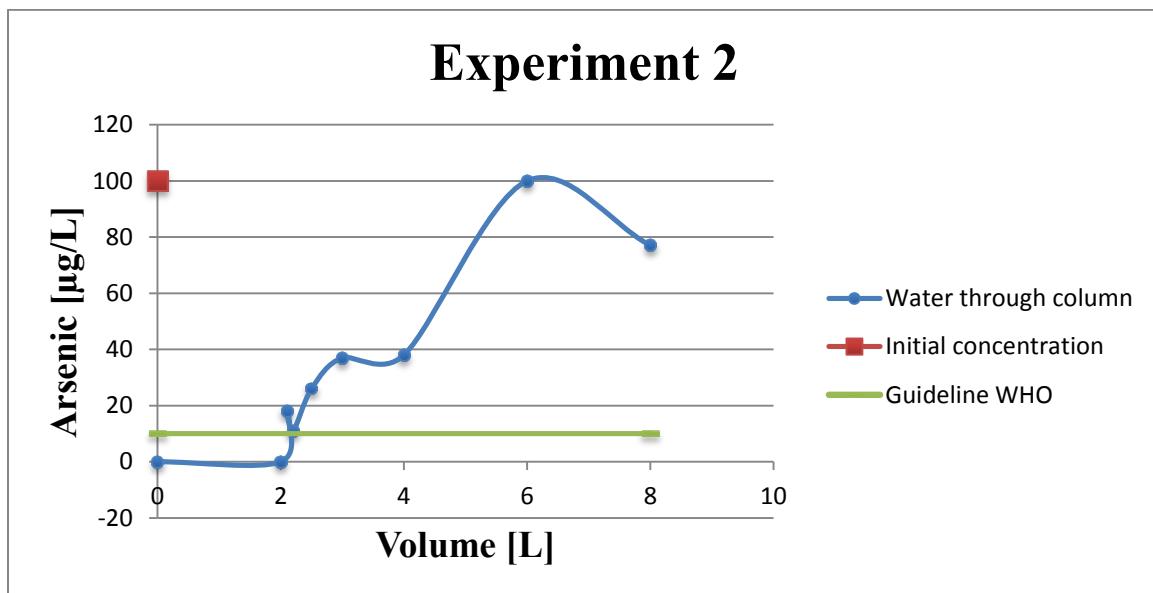


Figure 4: Experiment 2. The concentration of arsenic on outgoing water, initial concentration in the water and the guideline value of WHO. During the experiment an average flow of 0.5 L/h was used.

5.3 Experiment 3

The outgoing water was clear throughout the experiment and the last glass wool filter was white after that the experiment was finished. Water was collected 100 ml at the time, like in Experiment 2. Analyses were made after every 0.5 L. The concentration of arsenic in the outgoing water is demonstrated in Figure 5 bellow. An average flowrate of 0.5 L/h was used and the experiment was runned nonstop.

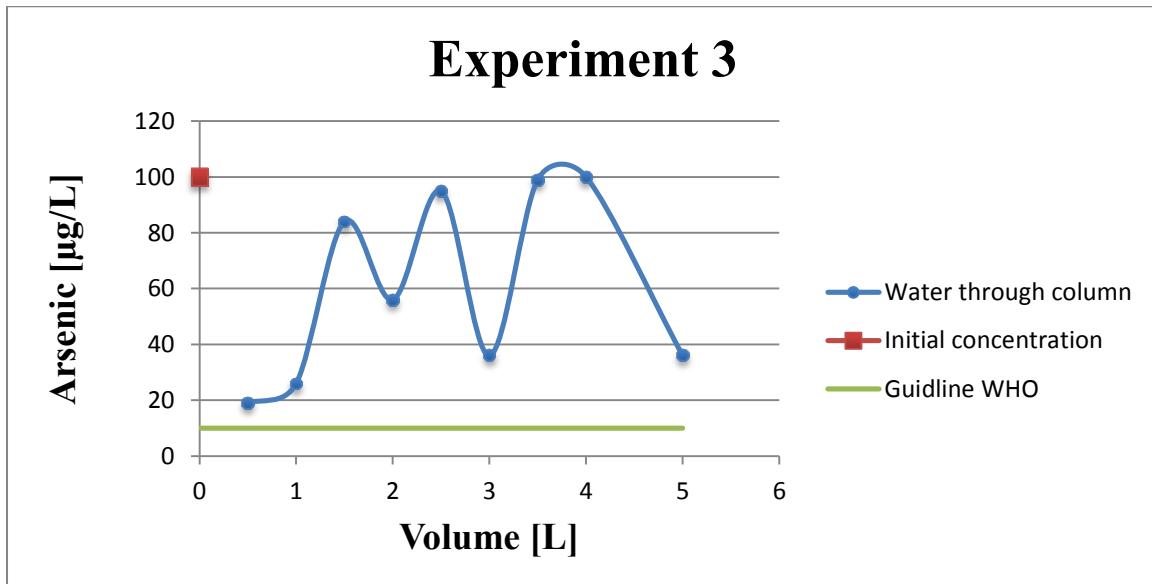


Figure 5: Experiment 3. The concentration of arsenic on outgoing water, initial concentration in the water and the guideline value of WHO. During the experiment an average flow of 0.5 L/h was used.

5.4 Experiment 4

Results from two adsorption tests are shown in Table 4 bellow. The water analysed was still colored orange from the ferrihydrite after the centrifugation.

Table 4: Results from two adsorption tests. The contaminated water was shaken and then centrifugated for 15 minutes. Initial concentration was before and concentration after test.

Adsorption test	Initial concentration [µg/L]	Concentration [µg/L]
1	250 000	>100
2	250 000	>100

The second centrifugation was made without success. No sedimentation had occurred and therefor no further analyses were made.

6 Discussion

Here follows a discussion based on the results from the experiments made in Burkina Faso. Application of the results made in Uppsala gave a successful first experiment, with no ferrihydrite leaking, in Burkina Faso.

6.1 Filter

A small scale prototype with glass wool as a filter was tested. With a flow not higher than 1.3 L/h, no ferrihydrite could be seen in the outgoing water. After that 8 L of water had passed through the column in Experiment 2, a higher concentration of iron could be detected in the outgoing than in the incoming water. It means that a small amount of ferrihydrite had leaked out but glass wool was still considered to work as a filter. When it comes to upscaling there might be some concerns. In the small scale test the filter was attached by hand. This was wished to be done in the same way every time to maintain the prototypes efficiency. This was hard and might be even harder for a larger scale. In a larger scale there is also a possibility that the water flow will be higher or the opening of the outflow wider. How this will affect the glass wool was not investigated but the use of glass wool during the project raised the question if any of these circumstances might damage the glass wool. An evaluation of other filters should be done comparing for example capacity, cost, availability and technical aspects.

6.2 Setup

Three experiments were made to investigate the capacity of ferrihydrite to adsorb arsenic using the setup. In Experiment 1 the concentration of arsenic in the outgoing water increased with the amount of water passing through the column. This correlation could not be seen as clearly in Experiment 2, where shorter intervals were examined and fluctuations could be seen. Experiment 2 was performed during four days, with a resting time after every two liters. Looking at the results from Experiment 2 no conclusion about regeneration could be made. In experiment 3, 5 L of water was let to pass through the setup without resting time. None of the outgoing water had a concentration bellow the WHO guideline. The result shows that big fluctuations occur. The fluctuations are hard to explain and show that this setup does not work properly with ferrihydrite

as adsorbent.

When the column with ferrihydrite was observed during running of the experiments, a small turbulence could be seen in the fluid. The turbulence always occurred at the same place, in the middle of the column. This raised the question whether the water takes a certain way through the column or not. A risk with that could be that the ferrihydrite particles in contact with the flowing water might lose their capacity to adsorb arsenic while the ferrihydrite in other parts of the column still have capacity to adsorb more. To investigate if increased flowrate or shaking of the column could create a larger turbulence and better adsorption could be an option.

6.3 Adsorption

In Uppsala the adsorption experiment showed a possibility for 1 g of ferrihydrite to absorb 0.07g arsenic. In Ouagadougou the same experiment was made to establish weather the capacity for ferrihydrite to adsorb arsenic is affected if other ions are present in the water. Unfortunately, the outcome did not give satisfying results. After centrifugation, the liquid taken for analyse was still orange. Analysis at the laboratory showed that the water contained more than 100 µg/L, the exact concentration could not be found with the instrument used. The experiment was made in the same way as in Uppsala and with the same proportions, however the outcome was not as positive. The reason could be that some ferrihydrite containing arsenic was still dissolved in the liquid that was analysed. Unfortunately, the second attempt of centrifugation failed. However, in Uppsala the water analysed was clear after centrifugation. It is therefore hard to make a conclusion whether the adsorption test made in Ouagadougou showed higher results than in Uppsala because of insufficient centrifugation or if it is because of the ions naturally occurring in the water used.

In Ouagadougou, two identical adsorption experiments were made parallel with the same outcome. A possible explanation of why the adsorption is less sufficient in the experiments made in Ouagadougou could also be that something went wrong during the preparation of the ferrihydrite used. What could be put against is that the two adsorption experiments were performed with two individually prepared ferrihydrite. If something affected the ferrihydrite during the preparation, results indicate that the same affection have occurred for two ferrihydrites.

6.4 Sedimentation of ferrihydrite

Sedimentation of the ferrihydrite in the solution was noticed early by the Uppsala group. The phenomena was used to clean the ferrihydrite, see collaboration with Uppsala. In Ouagadougou deionized water was used for washing instead of regular tap water. After addition of deionized water to the ferrihydrite the solution was shaken and then it was left to sediment. It was noticed that the sedimentation was not consistent. Sometimes the sedimentation occurred quick with distinct layers. Other times the water was still orange after a long time of resting. The discussions about what this depends on have been many. Due to difficulties to borrow a pH-meter, the solution of ferrihydrite had at some times been standing with the wrong pH-value over a longer time. The thought is that this might have affected the ferrihydrite.

6.5 Competitive ions

Comparing the initial concentration of phosphate with outgoing water in Experiment 2 in Burkina Faso, conclusions could be made that the original concentration was almost halved. This indicated that adsorption of phosphate had occurred. Since phosphate is a competitive ion with arsenic it is possible that phosphate affected the capacity of ferrihydrite to adsorb arsenic.

6.6 Source of errors

The original idea was to use water with naturally high concentrations of arsenic in Burkina Faso. This would have been ideal in order to examine how well the cleaning method works for this water. The collected water had lower concentrations of arsenic than expected, but was considered to be representative after addition of arsenic. The properties of the water used for experiments in Burkina Faso were compared with properties of water from the Province of Yatenga, where the concentration of arsenic in groundwater is generally higher. Results showed that same ions are present in the water collected as in the water from Yatenga, but that concentrations differ. However, in this study it was not investigated whether the content in the water also differ between wells in Yatenga. It is possible that the water content does not differ more between the used water and that in the Yatenga province, than between different wells in the same area.

Another source of error could be the accuracy of the analyse instruments used. The accuracy of the instrument used for analyses of arsenic was questioned, especially for higher concentrations

where it was suspected that all concentrations higher than 100 µg/L gave the result of 100 µg/L. That effects the results in the adsorption test when the ferrihydrite was shaken, the results showed 100 µg/L but if it is higher it is hard to know how much higher. It is therefore hard to make any conclusions of those results. It also means that the ingoing water in experiment 1,2 and 3 could have had a concentration higher than 100 µg/L.

6.7 Needs to be done in the future

To be able to use a solution of ferrihydrite for purification of water in the villages of Yatenga in Burkina Faso further research and development have to be done. For example, an upscaling of the setup with respect to available materials, filters, costs etc. is needed. It has to be investigated what a possible setup would look like and how big the capacity is thought to be when using it in field. Questions to answer is whether it is realistic to pump the water directly from the ground and should it then be used immediately or stored in a tank above or underground. If storing of water can be part of an upscaling of the setup, aspects as bacterial growth and water quality in the tank need to be evaluated. The next step could be to determine how the setup is optimized for ferrihydrite and if it is possible to create a flow that is high enough with sufficient purification.

A plan for maintenance of the full scale prototype needs to be developed. Knowledge of how to take care of the equipment and change the filter has to be transferred to the people living in the villages so that they can manage to keep the cleaning system running. It is also very important to develop a way to take care of used ferrihydrite with arsenic and the filters. It needs to be well organised, though waste management in Burkina Faso is today inadequate and need to be developed. A good idea is to investigate if the ferrihydrite can be regenerated or if the complete ferrihydrite needs to be deposited. Either way a plan for disposal of the collected arsenic is needed.

7 Conclusions

Adsorption tests made in Uppsala showed that ferrihydrite has a good capacity to adsorb arsenic. 1 g of ferrihydrite has a capacity to adsorb 0.07 g arsenic. This result was not confirmed by the adsorption test and experiments in Ouagadougou. The conclusion made is that the setup used is probably not ideal when using ferrihydrite for removal of arsenic. If it is possible to create a setup that better simulates the process of the adsorption test, ferrihydrite might have the possibility to be a suitable material for arsenic removal from water. Further research therefore needs to be done as a next step of the development.

Further investigations need to be done in order to decide the ideal proportions between ferrihydrite in the suspension and the volume of water in the column. The results show that the flow rate might affect the ability for ferrihydrite to adsorb arsenic, which could be limiting in a full scale prototype. Results with the setup in Ouagadougou showed that glass wool as a filter works for a long column and with a washed ferrihydrite. It has to be evaluated if it can work in a full scale prototype.

Regarding to its cost ferrihydrite is considered to be a good adsorbent under certain circumstances. Therefore further investigation should be done.

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9 Appendix

9.1 Appendix 1 - Ferrihydrite synthesis

Introduction

A description about the procedure of making the ferrihydrite suspension that will be used for removing arsenic from water.

Materials

1000, 500, 125 and 100 mL volumetric flasks

1500 ml PET bottle with lid

scale

pH electrode

pipettes

$\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$

deionized water

NaOH

HCl

Procedure

Day 1

The plastic bottle was placed on the scale and 29.1 g $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ was measured. Then 500 mL deionized water was added to the plastic bottle and the bottle was shaken throughly.

Meanwhile, 4 M NaOH was prepared by measuring 16 g NaOH in a 125 mL flask and then adding 100 mL deionized water so that the NaOH was dissolved.

The pH was measured to around 1.85 with a calibrated pH electrode. To raise the pH the 4 M NaOH solution was added with a pipette. Between each dose of NaOH the plastic bottle was shaken and pH was measured. This procedure was repeated until the pH reached 8. The bottle was then left to rest during 16 hours. 1 M HCl was prepared by taking 10 ml HCl (37%) and 90 ml deionized water.

Day 2

The plastic bottle was shaken again and pH was measured with the pH electrode. To reach pH 4.6 the 1 M HCl was pipetted into the bottle. Again, the bottle was shaken and pH was measured after each addition.

Results

750 mL aqueous suspension containing 6 g ferrihydrite.

References

Ingmar Persson, Professor at Department of Chemistry and Biotechnology, Swedish University of Agricultural Science.

9.2 Appendix 2 - Washing of ferrihydrite suspension

Introduction

Since the ferrihydrite suspension created as described in Appendix 1 contains very small particles, it is difficult to keep it from following the water through a filter made of glass wool. To remove the smallest particles from the ferrihydrite, the suspension was washed with regular water.

Materials

Ferrihydrite suspension

Deionized water

Procedure

By letting the ferrihydrite sediment in the suspension, the clear fluid that stayed on top could be removed by tipping the flask carefully. With this fluid the smallest ferrihydrite particles, that did not have enough time to sediment, was taken out of the suspension. After doing this, deionized water was added to the ferrihydrite suspension and the bottle was well shaken. The procedure of letting the ferrihydrite sediment and removing the top layer was repeated. This was done as soon as there was a clear difference between the two layers, even if the upper layer was not completely colorless. The suspension was washed this way for about six times.

Result

A ferrihydrite suspension without the smallest particles.

Discussion

It is impossible to know how big the smallest particles are in the suspension without doing measurements on the removed fluid. This was not done in this experiment, but can be useful later on to determine which particle size that is optimal. Large particles will not go through the filter, but for adsorbing arsenic smaller particles are more effective.

Conclusion

This way of washing the ferrihydrite suspension works well and it can easily be seen that it contains less small particles since it sediment much faster.

References

Gunnar Almkvist, Scientist at Department of Chemistry and Biotechnology, Swedish University of Agricultural Science.

9.3 Appendix 3 – Adsorption experiment in Uppsala

The adsorption test showed that 0.500 g As(V) could be added to a 1 L ferrihydrite suspension containing 10 g ferrihydrite with all As(V) adsorbed. When 0.800 g arsenic was added to the adsorption test, arsenic was detected in the clear and overlaying solution after the centrifugation. Measurements of absorbance and corresponding added amount of As(V) can be seen in Table A1.

Table A1: A table showing the measured absorbance with different amount of arsenic added to a solution containing 10 g ferrihydrite during nine batch-experiments. Arsenic detected only in the ninth batch-experiment, absorbance differs from zero (absorbance measured 0.15)

As(V) [g/L]	Absorbance
0.002	0
0.020	0
0.060	0
0.100	0
0.140	0
0.180	0
0.280	0
0.500	0
0.800	0.15

To be able to calculate the actual concentration of As(V) corresponding to the adsorption 0.15 a calibration curve was made. The absorbance of three known concentrations As(V) was measured, see Table A2.

Table A2: A table showing the arsenic concentrations for the calibration solutions and the responding absorbance measured

As (V) concentration [g/L]	Absorbance
0.000	0
0.025	0.05
0.100	0.18

The calibration points were used to create a calibration curve, see Figure A1. The result of the 0.8 g/L adsorption test was marked with a red dot. The absorbance of 0.15 responded to 0.084 g arsenic/L.

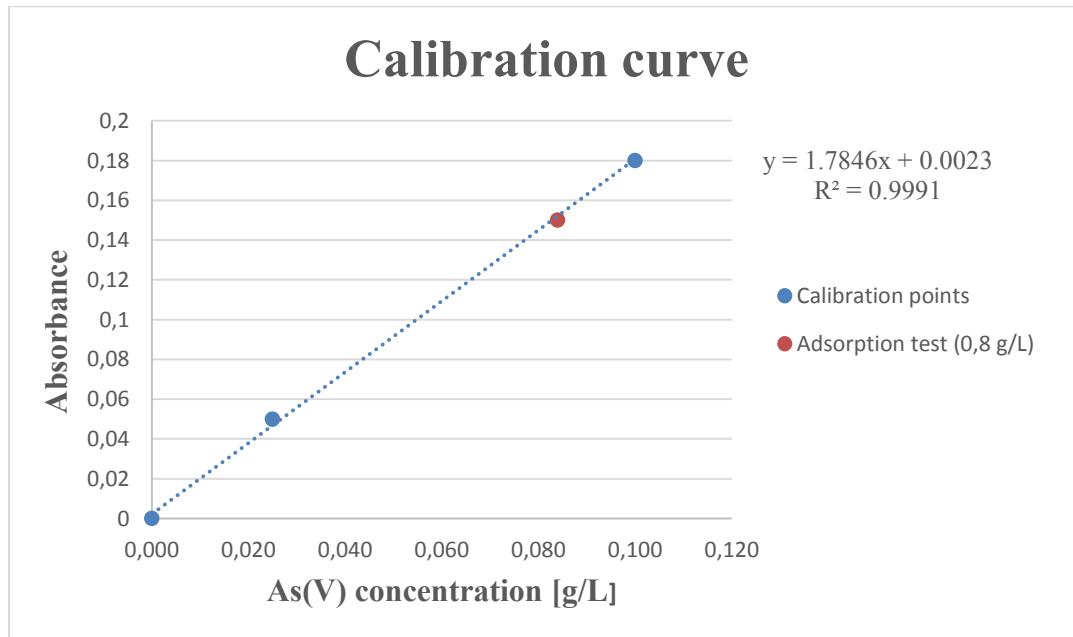


Figure A1: A visually description of absorbance in the 0.8 g/L batch experiment compared to the calibration solutions. A visually description of the absorbance measured (red point 0.084) in the 0.8 g arsenic/L adsorption test and the absorbances (blue points) for the calibration solutions. The equation for the calibration curve is shown as y.

The conclusion of the adsorption tests is that 1 L ferrihydrite suspension containing 10 g ferrihydrite can adsorb around 0.7 g arsenic, with a contact time of about 0.5 h. For calculations, see Appendix 4.

9.4 Appendix 4- Calculations Uppsala

To calculate the amount of As(V) corresponding to an absorbance of 0.15, the trend line from the calibration curve was used, see Figure A1 in Appendix 3. The trend line is referred to as equation 1 below. The value 0.15 was the absorbance when the ferrihydrite no longer adsorbed all As(V) in the water:

$$y = 1.7846x + 0.0023 \quad (2)$$

$$\frac{y-0.0023}{1.7846} = x$$

$$y = 0.15 \rightarrow x = 0.084 \text{ g/L}$$

$\therefore 0.084 \text{ g/L As(V)} \text{ correspond to an adsorbance of } 0.15$

To estimate the amount of As(V) adsorbed by the 10 g ferrihydrite (Fh) solution used in the 0.8 g arsenic /L batch experiment, the difference between the initial and remaining concentrations of As(V) was calculated.

$$0.8 - 0.084 = 0.716 \text{ g}$$

$\therefore 10 \text{ g Fh adsorbs } 0.716 \text{ g As(V)} \rightarrow 1 \text{ g Fh adsorbs } 0.0716 \text{ g As(V)}$

Calculations of the theoretical As(V) adsorption for the previous test described in *Method Uppsala - Running the experiment* with 0.1 g/L As(V) solution:

1 g Fe(NO₃)₃ · 9H₂O contains 0.138 g Fe \leftrightarrow 0.208 g Fh

29.1 g Fe(NO₃)₃ · 9H₂O \leftrightarrow 6.0528 g Fh

$$6.0528 \text{ g Fh} * 0.0716 = 0.4333 \text{ g} \approx 0.4 \text{ g}$$

\therefore The theoretical adsorbance capacity of the Fh in the column, 6 g, would have adsorbed around 0.4 g As(V)

9.5 Appendix 5 – Results Experiment 2 and 3

The values used to create Figure 4 and Figure 5 are shown in Table A3 and Table A4 below.

Table A3: Experiment 2. Arsenic contaminated water was led through a column containing a suspension of ferrihydrite. The arsenic concentration after were measured after different volumes going through the column.

Volume water [L]	Arsenic concentration [$\mu\text{g/L}$]
0	100
2	0
Rest: 17 hours	
2.1	18
2.2	11
2.5	26
3	37
4	38
Rest: 22 hours	
6	100
Rest: 14 hours	
8	77

Table A4: Experiment 3. Arsenic concentration after different volume going through the column

Volume water [L]	Arsenic concentration [$\mu\text{g/L}$]
0	100
0.5	19
1	26
1.5	84
2	56
2.5	95
3	36
3.5	99
4	100
5	36