ENHANCING THE CAPACITY OF SEEDS AS TURBIDITY REMOVAL AGENTS IN WATER TREATMENT

A minor field study

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This study has been carried out within the framework of the Minor Field Studies Scholarship Programme, MFS, which is funded by the Swedish International Development Cooperation Agency, Sida.

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The International Relations Office at KTH the Royal Institute of Technology, Stockholm, Sweden, administers the MFS Programme within engineering and applied natural sciences.

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Enhancing the capacity of seeds to remove turbidity in water treatment

ABSTRACT

The aim of this master’s thesis was to investigate if defattening of Parkinsonia aculeata (in swahili “mkeketa”) and Vigna unguiculata (in swahili “choroko”) would enhance the capacity of the seed’s properties in removing suspended particles from surface water. The seeds are used in local traditional treatment of drinking water in Tanzania. The aim was also to investigate the possibility to reduce high concentrations of fluoride with the seeds. The seeds contain proteins that act as coagulants. Coagulated particulate matter can be flocculated and separated from the water. A purification of the coagulants by defattening was expected to enhance the coagulating capacity. Experiments were conducted in jar-tests with dosages of coagulant solutions of undefattening and defattened seed solutions and alum (aluminium sulphate). The experiments showed that both Parkinsonia aculeata and Vigna unguiculata seeds can compete with alum in drinking water treatment of surface water, reaching the same or better final results in turbidity removal. Both seeds also produce less sludge volumes than alum and functions in turbidity removal together with alum. The seeds may be used as coagulant aids to reduce the usage of chemicals and sludge production. They were not able to clarify turbid waste water and did not reduce high concentrations of fluoride in groundwater. Further, the turbidity-removal capacity of the coagulants had reduced capacities in water with low pH-values.

Key words: drinking water treatment, natural coagulants, Parkinsonia aculeata, Vigna unguiculata
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List of Abbreviations

alum  Aluminium sulphate
COD   Chemical Oxygen Demand, a measure of the organic compounds in water [mg/L].
CSE C  Crude seed extract of *Vigna unguiculata* (*swa. choroko, eng. cowpea*)
CSE P  Crude seed extract of *Parkinsonia aculeata* (*swa. mkeketa, eng. jerusalem thorn*)
dCSE C Defattened crude seed extract of *Vigna unguiculata*
dCSE P Defattened crude seed extract of *Parkinsonia aculeata*
NTU   Nephelometric Turbidity Unit, a measure of the amount of light scattering particles in a solution.
TDS   Totally Dissolved Solids [mg/L].
1 Introduction

The everyday experience of water supply for many Tanzanians is discontinuous operation, breakdowns, droughts and poor water quality. The overall water supply coverage was estimated to 42% of the population in rural areas and 80% in urban areas in year 2000 by the World Health Organization and United Nations Children’s Fund (WHO and UNICEF, 2000). The figures are based on the availability of a minimum of 20 litres water per person and day within 1 kilometer from the user’s home. Adequate water supply and sanitation are crucial to our health and by improving supplies of water and sanitation, valuable social and economical benefits are gained.

The irrigation systems in Tanzania are important to a wide range of activities. The traditional trench systems are important for the domestic supply for the animals as well as for irrigation, transport, fishing and hydropower. Risks of polluting water supplies is generally a concern for commercial agriculture where the risks involve siltation and chemical pollution (e.g. in sisal production). A growing problem is mercury contamination from gold mining. Currently, a majority of the drinking water is taken from surface sources, but there is an increasing use of groundwater in rural and urban areas with an increasing risk of contamination from pit latrines (Maganga et al, 2002).

Tanzania adopted the UN goals for the water decade in 1980 and mobilised external assistance to prepare regional water plans and to facilitate rapid construction of water supply projects. Little attention was given to the ownership of the systems. Over 90% of the piped water supply projects ceased operating, often because of lack of fuel and service of pumps and motors to keep them running. Most of the hand-pumps for shallow wells also stopped operating due to lack of maintenance. Attempts to solve the problems involve handing over the operation responsibilities of running small water supply systems to the village governments. Larger systems remain within the regional and national authorities responsibilities (Maganga et al, 2002).

Scarcity of water forces large populations to rely on unsafe water resources that may be muddy or cloudy (turbid) and contaminated by animals and humans (Marobhe, 2008a). Developing existing resources is problematic due to international interests of the great lakes bordering to neighbouring countries and deep groundwater tables in dry regions requiring substantial investigations and investments (WHO and UNICEF, 2000). Control of the sources of water together with treatment of drinking water in remote areas where the infrastructure has not yet reached, is part of the solution to improve the life for many people.
1.1 Treating water

Safe drinking water should generally be free from heavy metals, turbidity, organic compounds and pathogens. Turbidity may contain these compound and also shield pathogens from chemical or thermal damage. It is also important to remove turbidity for the aesthetic values of the drinking water. Organic substances in water might originate from industrial and agricultural operations, which contribute with compounds such as chloroform, gasoline, pesticides and herbicides. Finally, protozoa, bacteria and viruses are all pathogens that can cause diseases (Chermisinoff et al, 2002).

Conventional treatment of water often include coagulation, flocculation, sedimentation, filtration and disinfection. Coagulation is the destabilization of particles, which means a changed state in the dispersion of colloidal particles (dissolved particles with a size between 1 nm and 1 µm). The stability of colloids is dependent of their surface charge, why the stability of the particles can be affected by electrolytes and adsorbates that affect the surface charge of the colloids. Polymers can affect the particle interaction by forming bridges between them or by sterically stabilizing them (Stumm and Morgan, 1996).

Among the coagulating agents used in water treatment, ferric sulphate or alum (aluminium sulphate) is some of the most widely used salts. The salts acts as coagulants by neutralizing the charges of colloidal particles, adsorb or trap them and facilitate the agglomeration of particles during slow mixing provided in flocculation (WHO, 2008).

Aluminium ions have a high positive charge which bind to negatively charged particles and humic compounds and form “bridges” between them, creating larger particles that may settle or be removed by filtration. With an optimal operation and dosage of alum, the residual aluminium concentrations may be lower than the initial concentrations, but the usual case is increasing concentrations. Aluminium is strongly neurotoxic and may be involved in the development of Alzheimer’s disease. Uptake of aluminium through drinking water is expected to be low, due to the poor capacity of absorbing aluminium by the gastrointestinal tract. The possible existence of bioavailable aluminium in drinking water can nonetheless be completely dismissed (Flaten, 2001).

There are also issues concerning aluminium in acid waters with acute toxicity to fish. Aluminium bind to functional groups in the gills of the fish and affect the permeability of the membrane. This induce an accelerated cell-death which leads to a high mortality in fish populations (Exley et al, 1991).

Alum is manufactured in a simple two-step process where aluminium trihydrate and sulfuric acid are first mixed and then crushed into suitable pieces to be sold. Aluminium trihydrate is purified from bauxite, which is a non-renewable resource. Commercial bauxite deposits occur in Australia, Jamaica, France, Guyana,
Guinea, USA and Brazil. Bauxite ore is dissolved in strong caustic soda whereby aluminium trihydrate may be precipitated. The major potential environmental hazards posed by production of alum is the risk of changing the pH in surrounding water sources (Donaldson and Robertson, 2008).

When coagulation and filtration are well designed and operated, other steps in the treatment system may be scaled down (Ghebremichael, 2004).

The efficiency by which the contaminants are removed in drinking water treatment depends on the quality of the raw water, coagulants, mixing conditions and pH. Small-scale batch coagulation tests, jar tests, are often used in water treatment plants to control the optimum dosage of coagulants and pH in the treatment process (WHO, 2008).

High levels of fluoride is a concern in both ground and surface waters in Tanzania. Cases of dental and skeletal fluorosis are common in the northern and central parts of the country (Mjengera and Mkongo, 2003). Fluoride levels of 1-1.5 mg/L strengthens the enamel (Mohapatra et al, 2009), higher concentrations or a prolonged exposure to elevated concentrations result in damage through dental and skeletal fluorosis, where the lustre of teeth enamel is lost and fluoride is deposited in joints of neck, knees, shoulder bones etc., making it difficult to move or walk. Fluorosis may also cause muscle fibre degeneration, low haemoglobin levels, headache, neurological manifestations, etc. (Meenakshi and Maheshwari, 2006).

Fluoride is a strongly electronegative element and is easily attracted by positive charged ions, such as calcium. Defluoridation methods in water treatment are based on the mechanisms of adsorption, ion-exchange, precipitation-coagulation, membrane separation, electrolytic defluoridation and electrodialysis, etc. Activated alumina is commonly used for adsorption of fluoride. The adsorption mechanism is affected by hardness and the dosage of the activated alumina. The process is pH specific and should have a pH between 5 and 6. At higher pH, silicates and hydroxides becomes stronger competitors of the ion exchange sites on the activated alumina, at pH below 5 the alumina is dissolved. In ion-exchange a basic anion-exchange resin containing ammonium functional groups is able to replace a chloride ion realted to the functional groups with a fluoride ion. The coagulation-precipitation method use lime and alum in combination, calciumhydroxide reacts with fluoride ions creating insoluble calcium fluoride. Membrane processes use pressure to remove dissolved solids, including fluoride ions (Meenakshi and Maheshwari, 2006).

1.2 Local treatment of drinking water with natural coagulants

Women in areas suffering from serious water supply shortage in rural and peri-urban areas of Tanzania traditionally treat water from wells and small ponds using seed powder of different locally avail-
able plants. The seeds used mainly belong to *Vigna unguiculata* (eng. Compea), *Voandzeia subterranea* (eng. Bambara groundnut), *Arachis hypogaea* (eng. Peanut), *Vicia faba* (eng. Field bean), *Parkinsonia unguiculata* (eng. Jerusalem thorn) and *Zea mays* (eng. Maize) (Marobhe et al, 2007c). The plants act as clarifiers of turbid water where the initial turbidity values may range between 2250 and 5250 NTU (Nephelometric Turbidity Units) and have bacterial counts between 900 and 1500 faecal coliforms per 100 mL (Marobhe, 2008c).

The seeds from the plants are ground to a fine powder, which is mixed with the turbid water, the flocs formed are then left to settle before decantation and usage. Good clarification hasn’t always been obtained due to lack of knowledge on how the seed powder coagulates turbid water. By studying the seeds used in these traditional water treatment methods scientifically, it has been anticipated that achieved knowledge on the functionality of the seeds may not only provide benefits for the rural population, but also the urban water utilities which often produce insufficiently treated water (Marobhe, 2008c).

Studies on other natural coagulants (e.g. *Moringa oleifera*) in water treatment has shown an increased organic content in the treated water. This is problematic due to the fact that organic matter might enhance a chlorine demand and at the same time generate trihalomethanes (which are cancerogenic) during the disinfection with chlorine. It has therefore been suggested that the active proteins should be purified prior to usage in water treatment (Ndabigengesere and Narasiah, 1998; Okuda et al, 2001; Ghebremichael et al, 2006).

### 1.3 Objectives

*Vigna unguiculata* and *Parkinsonia aculeata* are two of the mainly used plants in water treatment in rural areas of Tanzania. Both plants contain proteins that are active in water treatment processes. They have been purified in earlier studies by ion exchange chromatography (Ghebremichael et al, 2006), a method which require specialized knowledge and equipment. Alternative, cost effective methods should be sought after. In the light of this problem it is hypothesized that defattening of the seeds could increase the efficiency in treatment of turbid waters. Further the objectives of this study aims at examining whether the seeds could be used in large scale exploitation.

Another concern regarding water pollutants in Tanzania is high levels of fluoride in drinking water. Therefore this study also aims to investigate the possibility of using the seeds in removal of fluoride in drinking water.
2 Plant materials in water treatment

Natural materials have been used by humans throughout history in treating drinking water. When chemical salts were introduced to the market, natural materials were abandoned as coagulating agents. The traditional treatment methods have not been able to compete efficiently with chemical salts due to lack of scientific knowledge on how the materials function. The use of natural coagulants of vegetable and mineral origin have survived in parts of the world where modernization has not reached (Ndabigengesere and Narasiah, 1998).

Issues concerning handling of chemicals and sludge has awoken an interest for plant-based materials as alternatives to chemical coagulants in water treatment. Several plant-based coagulants have been studied scientifically, some of them are listed here: Seeds of Strychnos potatorum (eng. Nirmali), a tree found in India, Sri Lanka and Burma contain anionic polyelectrolytes that destabilize particles through interparticle bridging. Sanskrit writings imply that Strychnos potatorum has been used to clarify turbid surface waters for over 4000 years (Yin, 2010). Moringa oleifera (eng. Drumstick tree), is a tropical plant found in Asia, Sub Saharan Africa, Latin America. Moringa oleifera has coagulant properties related to dimeric cationic proteins. The main mechanisms for coagulation is adsorption and charge neutralization (Ndabigengesere et al, 1994). Vigna unguiculata and Parkinsonia aculeata are plants containing cationic proteins which are active in coagulation of turbid waters.

2.1 Parkinsonia aculeata

*Parkinsonia aculeata* is a well known plant in the Singida district in Tanzania, where it is grown as a food crop, for medicinal usages, feed for livestock, as an ornamental plant etc.

It is a short shrubby tree which can reach a height of 10 m. It belongs to the Fabaceae family. It has yellow fragrant flowers that are pollinated by bees and give fruits carrying one to several seeds. The tree is widespread over the world and has many names (e.g. jerusalem thorn, horse bean, palo verde, mataburro, madam naiz and arrête boeuf) (Francis, 2009). The vernacular name in Tanzania is “mkeketa” (Marobhe, 2008c).

*Parkinsonia aculeata* will grow in many different soils, in everything from sand dunes, clay soils, strongly alkaline, chalky and mildly salty soils. It is heat resistant and can survive in dry areas with an annual rainfall of less than 300 mm. The tree is sensitive to temperatures below $-8^\circ$C.

The tree produce two different type of seeds, about 25 % of them are soft and will germinate without pretreatment, the rest have hard seed shells and requires processing to germinate (transportation through water or animals), see figure 1. The plants live to be about 30 years old (Francis, 2009).
2.2 Vigna unguiculata

*Vigna unguiculata* (eng. “cowpea”, swa. “choroko”) is an annual legume plant. It is well known in Tanzania as a food crop and for animal fodder.

The plant originates from Africa and has a history in farming ranging back as far as 5-6 thousand years. The flowers are mostly self pollinating and give pods carrying the seeds. The plant can be used in all stages of growth; the green leaves and immature snapped pods and green seeds are used as vegetables and mature, dried seeds (see figure 2) can be stored and used in cooking or as fodder.

*Vigna unguiculata* can be used as a nitrogen fixing crop and for erosion control. It grows in warm and dry conditions, with temperatures above zero. The crop is preferably grown well-drained, sandy loams or soils. *Vigna unguiculata* is drought resistant, which makes it an important crop in many underdeveloped parts of the world. Mature green seeds are normally harvested mechanically by some type of mobile viner (Davis et al, 1991). For more information regarding the local knowledge on growth and usage of *Vigna unguiculata* in Tanzania, see the interview in Appendix I.

2.3 Coagulating properties

The active agents of *Parkinsonia aculeata* and *Vigna unguiculata* are expected to be at least two different coagulating proteins with a molecular weight of about 6 kDa (Marobhe et al, 2007b). The hypothesized mechanism of coagulation is adsorption and charge neutralization of colloidal particles, similar to the main mechanisms of the widely studied *Moringa Oleifera* (Ndabigengesere and Narasiah, 1998; Okuda et al, 2001; Ghebremichael et al, 2006; Ghebremichael, 2004).

The traditional way of preparing the seeds are to grind them to a fine powder which can be stored for a daily usage up to 2 months.
Figure 2: Dry, mature seeds of Vigna unguiculata.

A plastic 20 litre bucket with water is usually dosed with 2 to 5 tea-
spoons (approximately 20 to 50 grams) of seed powder and mixed
with a velocity of about 100-150 revolutions per minute (RPM) and
is thereafter allowed to swirl for 5-10 minutes after which formed
flocs are allowed to settle for 20 to 25 minutes. The clarified water
is decanted and stored in a cool place for drinking and cooking pur-
poses. An average household purifies 1 to 3 buckets per day. The
rapid and slow mixing followed by settling is similar to conventional
surface water treatment (Marobhe et al, 2007c).
3 METHODOLOGY

The tests are planned as jar-tests with river surface water, as it is a common source of drinking water that may need turbidity reduction. Groundwater from a drilled well containing high levels of fluoride is also tested to examine whether it is possible to reduce the fluoride concentration.

Coagulants may vary in efficiency depending on the source of water, why comparison tests were made with synthetic turbid water. Waste water is also tested to examine whether a high organic content of the treated water has an impact on the effectivity of the seeds.

3.1 Equipment and coagulation procedure

Coagulation-flocculation experiments were conducted with jar test equipment (model Phipps and Bird - PB-700TM), see figure 3. The jar test rig is equipped with six glass beakers, each equipped with a stirring paddle. The stirring speed of the paddles is set manually with a knob and the beakers are tested simultaneously.

All coagulation-flocculation tests were set up using 500 mL water samples. One of the six beakers in the test rig was left without treatment to provide control. The water samples were dosed with coagulant solution by pipetting. A rapid mixing period of 150 RPM during 5 minutes was followed by slow mixing at 40 RPM during 25 minutes, allowing coagulation and flocculation to occur. A 30 minutes long settling period followed to allow formed flocs to sink to the bottom of the beakers and the residual turbidity was measured with spectrophotometer, see Appendix III for specification. All parameters measured in each beaker are collected between the water surface and the bottom of the beaker (3 cm under the water surface) using a syringe to avoid disturbance of the samples.

3.2 Preparation of coagulants

Seeds of *Vigna unguiculata* were purchased at Magomeni market in Dar es Salaam. The seeds of *Parkinsonia aculeata* were picked from a tree growing in Tegeta ward in Dar es Salaam.

Figure 3: Jar test equipment in action.
3.2.1 Crude seed extracts

Crude seed extracts (CSE) were prepared with good quality seeds of *Vigna unguiculata* and *Parkinsonia aculeata* by crushing the seeds, separating the kernel from the shell and grinding the kernels to a fine powder. The powder was then sieved through a tea strainer to derive a fine, even powder.

The seeds of *Vigna unguiculata* were crushed in a kitchen blender and the mixed powder of kernels and shells were moved to a plate that was shaken by hand to separate the kernels from the shells. The kernels were then ground to a fine powder in the blender. The seeds of *Parkinsonia aculeata* were crushed one by one using a cast-iron stick on a stone board, whereby the kernel could be separated and ground into a powder using a pestle and mortar. The powders were used within one week after preparation.

3.2.2 Defattened crude seed extracts

Defattened crude seed extract, dCSE, was prepared by mixing crude seed extracts with 70 % ethanol. A mass/volume ratio of 1:4 was used, where two grams of powder was mixed with 8 mL of 70 % ethanol for 20 minutes with a magnetic stirrer. The solution was left to stand still for approximately 1 hour, whereby the ethanol/oil phase had separated from the coagulant phase and could be removed with a syringe. The defattened crude seed extract (dCSE) was spread on a plastic plate and left to dry for at least one night, until completely dry. The dried dCSE was thereafter ground with mortar and pestle to create a fine powder.

3.2.3 Extracting active components

Solutions of crude seed extracts and defatted crude seed extracts were prepared according to Marobhe et al (2007a), to obtain the active coagulants: One gram of powder was suspended in 100 mL of distilled, deionized water creating a 1 % w/V seed solution. The solutions were stirred for 20 minutes at room temperature (approximately 26°C) using a magnetic stirrer to extract coagulating components. The solutions were then filtered through a cloth of titron (a material used as lining in Tanzanian dresses) twice before using the filtrate in coagulation experiments to remove larger particles that could interact with the coagulants. The seed solutions were stored in refrigerator for maximum one week.

3.2.4 Alum

Alum was used in comparing experiments and used as primary coagulant during experiments with CSEs and dCSEs as coagulant aids. The aluminium sulphate was crushed to a powder using mortar and pestle before dissolving it in distilled, deionized water to a 1 % weight to Volume (w/V) solution using a magnetic stirrer.
3.3 Estimation of protein concentrations in solutions of natural coagulants

The protein concentration was estimated using the Bradford protein assay with bovine serum albumin as standard (Bradford, 1976). The method is based on the observation that the dye coomassie brilliant blue exists in two different color forms. The dye is used to stain proteins, whereby the red form of the dye is converted to blue upon binding to protein.

A wavelength-absorbance method was used to control the results obtained from the Bradford protein assay. A standard curve was used for the Bradford method, which had been prepared by plotting the weight of protein against corresponding absorbance, to determine protein concentrations in unknown samples.

Two sets of tests were made for both methods and the average values were used to calculate the concentration in each seed solution.

3.4 Turbidity measurement

Removal of turbidity was measured after a 30 minute settling period after coagulation and flocculation. Water was collected with a syringe 3 cm below the water surface (in the middle of the water column), not to disturb the sample.

Standard deviations on the variations of turbidity removal for the seed solutions and alum were based on jar-tests with initial turbidities of 400 NTU. The equation used to calculate the standard deviation, \( s \), is shown in equation 1 (Blom et al, 2005):

\[
s = \sqrt{\frac{1}{n-1} \sum_{j=1}^{n} (x_j - \bar{x})^2}
\]  

3.5 Water samples

3.5.1 Surface water

River water from upper Ruvu (Ruvu juu) was collected in 25 litre plastic containers and brought to Ardhi University, where the quality of the water was examined.

The water was collected close to the shore under a traffic bridge on the upper side of Ruvu juu water treatment plant, one of two water treatment plants providing Dar es Salaam with water, see figure 4. The water was collected at three different dates during the short rains period in October and November. The sediments were disturbed during collection to increase the turbidity of the water. Collected water was kept cool in a refrigerator at Ardhi University.

Water samples with turbidities of 250, 400, 750 and 2000 NTU were prepared in the laboratory by mixing tap water with muddy river water. Tap water was used due to limited amounts of distilled
water. The tap water originates from the Ruvu river. Comparing experiments were also conducted with river water prepared by mixing clear river water with muddy river water. Water samples with turbidity of 2000 NTU were left for 5 minutes to allow larger particles to settle before the turbidity was measured prior to the testing.

3.5.2 Synthetic turbid water

To test water with different turbidities with low amounts of organic compounds, turbid water was artificially prepared according to Antov et al (2009), by mixing 10 gram of Capim TM kaolin with 1 litre distilled, deionized water to a 1 % w/V stock solution. The solution was stirred with a magnetic stirrer for 1 hour to achieve uniform dispersion of kaolin particles and was left to stand for 24 hours before usage for completing hydration of the particles. Stock solution was mixed with tap water to obtain water with correct turbidity for each new jar-test.
3.5.3 Water with high fluoride content

Experiments on water with high levels of fluoride was conducted on groundwater collected from a drilled well in Arusha. The water had a natural concentration of 8.71 mg Fluoride per litre. The water was collected in a plastic container and was transported by public long distance bus to Dar es Salaam. All water parameters were measured the day the water arrived, except fluoride concentration, which was conducted two days later. The water was not diluted during the experiments. The water was stored in room temperature.

3.5.4 Waste water

Waste water was tested to examine the functionality of the seeds in waters with raised organic content, here with a COD of 262 mg/L. Waste water was collected twice from Ardhi University’s sewage system in a control chamber after the coarse grid in the first treatment step. The waste water was kept in a 25 litre container and was at both times used within one day from collection. The water was not diluted during the experiments and was kept in room temperature.

3.6 Coagulant dosing

The seed solutions were tested at varied initial turbidities to examine the activities of the coagulants. Coagulants were initially added to the six beakers with dosages of 0, 0.5, 1.0, 2.0, 3.0, and 4.0 mL of 1 % w/V solutions for turbidities of 250, 400 and 750 NTU. Turbidities of 2000 NTU were initially tested adding 0, 2.0, 4.0, 6.0, 8.0 and 10 mL 1 % w/V solutions. An optimized dosage was achieved through planning the next jar-tests with smaller steps in coagulant dose between the beakers, until the dose differed 0.1 mL between the beakers. Alternatively when the residual turbidity differed with 1-2 NTU between the beakers, or more tests were impossible to conduct due to the lack of water samples or lack of natural coagulant solutions.

The effect of the coagulants was compared to the reference beaker in each jar-test to see how much the coagulants improved the turbidity removal in addition to the flocculation process. The increased turbidity removal achieved by dosing coagulants to the beakers was estimated by comparing the optimized beaker with the reference beaker as a percental difference in turbidity removal.

3.7 Coagulant aids

Tests were made on surface water with a turbidity of 2000 NTU and on waste water with a turbidity of 118 NTU. Alum was used as primary coagulant with the seed solutions as coagulant aids. A low dose of alum was chosen according to earlier optimization tests and was dosed to each beaker, including the reference beaker.

The dosages of coagulant aids were chosen according to earlier obtained optimal dosages of natural coagulants for surface water and...
waste water. The new dosages were varied around the optimum to find the new optimal dosage for alum with coagulant aid.

3.8 Dependence of pH

The efficiency of the coagulants was tested with varying pH-values in surface water with turbidity of 400 NTU and water with high levels of fluoride. Tests were run with natural pH values (pH 7.61-8.30) and with low pH-values (pH 5 and 6). pH 5 and 6 were obtained through acidification by adding a lemon salt (in swahili “chumvi limao”).

3.9 Water parameters

Most of the water parameters were measured the same day as the water was collected. An exception was the ground water from Arusha (used in tests on fluoride-removal), where the water arrived at Ardhi University approximately 4 days from the date of collection. Water samples, CSE-, dCSE- and alum solutions were in some cases diluted with distilled water when the measured concentrations were too high to read with the method used (measurements of iron, phosphate and chemical oxygen demand, COD).

All turbid water samples used in the jar tests were controlled to have correct turbidity before the experiments were started with spectrophotometer, specification see Appendix III. The spectrophotometer was also used to determine COD, derived by using the mean value of two measurements. HACH buffer pillows were used with the spectrophotometer to measure nitrite, iron, phosphate, sulfate and total hardness (calcium and magnesium ions), see Appendix III.

Titration was conducted to determine alkalinity, occurrence of phenol, hardness (calcium ions), total hardness and chloride. The HACH Digital Titrator Test Kit Cat. No. 16900-01 was used together with HACH Digital titration cartridges.

pH and temperature was determined with HACH HQ30d flexi pH-meter. Electric conductivity, totally dissolved solids (TDS) and salinity was determined with HACH SensIon 156. Concentrations of Fluoride was determined with HACH Fluoride Electrode with HACH Buffer pillows, see Appendix III.

3.10 Sludge

The volume of sludge produced during the experiments was measured for the optimum dosage of coagulants compared to the reference beaker. The clear water phase from the reference beaker and the beaker with clearest water was decanted into bottles after all water parameters were read, whereby the sludge phase was poured onto glasscylinders. The volumes of sludge was read visually after 30 minutes and 60 minutes.
4 Results

4.1 Coagulation procedure

The set up of the coagulation-flocculation tests were straightforward and the effect of the coagulants could be studied in all stages of the process, from formation of flocs during mixing to settling of formed particles.

4.2 Quality of coagulant solutions

Coagulant solution of defattened Parkinsonia aculeata was by accident only filtered once before a coagulation-flocculation test, with the consequence that the residual turbidity at best reached 23 NTU. The best result was 9 NTU for the exactly same set-up after a second filtration, an increased efficiency of 9%.

Estimated protein concentrations are given in table 1. The crude seed extracts of the different seeds are for short called CSE and defattened crude seed extracts dCSE in the tables. The type of seed is given as P for Parkinsonia aculeata; CSE P and dCSE P. And C for Vigna unguiculata (C as in en. cowpea or sw. choroko); CSE C and dCSE C.

Measured parameters of the coagulant solutions are given in table 2. The largest differences between undefattened and defattened seed solutions are that the defattened seed solutions all have lower values of electric conductivity, TDS, salinity, alkalinity, total hardness and chloride than undefattened seed solutions. All parameters were measured on seed solutions prepared the same or the previous day. The COD-values were diluted 20 times when measuring. COD in table 2 are calculated from the measured value and are reduced with 11% for the defattened seed solutions compared to the undefattened seed solutions. The COD-values are much higher for the natural coagulants than the aluminium sulphate, with values of 4320-5740 mg/L, the same value for alum is 100 mg/L. Alum also have lower values of pH (3.6), electric conductivity, alkalinity and hardness than the solutions of natural coagulants.

Table 1: Concentrations of proteins in solutions of crude seed extracts and defattened crude seed extracts of Parkinsonia aculeata (CSE P, dCSE P) and Vigna unguiculata (CSE C, dCSE C).

<table>
<thead>
<tr>
<th>Coagulant</th>
<th>Protein concentration [mg/mL]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSE C</td>
<td>1.4</td>
</tr>
<tr>
<td>dCSE C</td>
<td>1.9</td>
</tr>
<tr>
<td>CSE P</td>
<td>2.8</td>
</tr>
<tr>
<td>dCSE P</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Table 2: Measured parameters of the coagulant solutions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>CSE C</th>
<th>dCSE C</th>
<th>CSE P</th>
<th>dCSE P</th>
<th>Alum</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td></td>
<td>7.0</td>
<td>7.1</td>
<td>6.8</td>
<td>7.0</td>
<td>3.6</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>22.2</td>
<td>21.6</td>
<td>22.7</td>
<td>22.6</td>
<td>22.4</td>
</tr>
<tr>
<td>Electric conductivity</td>
<td>µS/cm</td>
<td>360</td>
<td>262</td>
<td>441</td>
<td>248</td>
<td>3</td>
</tr>
<tr>
<td>TDS</td>
<td>mg/L</td>
<td>180</td>
<td>131</td>
<td>205</td>
<td>124</td>
<td>1501</td>
</tr>
<tr>
<td>Salinity</td>
<td>%</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>1.6</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>mg/L</td>
<td>620</td>
<td>100</td>
<td>1000</td>
<td>980</td>
<td>&lt;20</td>
</tr>
<tr>
<td>Hardness, Ca²⁺</td>
<td>mg/L</td>
<td>300</td>
<td>100</td>
<td>100</td>
<td>140</td>
<td>37.5</td>
</tr>
<tr>
<td>Total hardness, Ca²⁺ Mg²⁺</td>
<td>mg/L</td>
<td>2000</td>
<td>400</td>
<td>600</td>
<td>160</td>
<td>387.5</td>
</tr>
<tr>
<td>Chloride, Cl⁻</td>
<td>mg/L</td>
<td>620</td>
<td>520</td>
<td>200</td>
<td>340</td>
<td>987.5</td>
</tr>
<tr>
<td>COD</td>
<td>mg/L</td>
<td>4840</td>
<td>4320</td>
<td>5740</td>
<td>5080</td>
<td>100</td>
</tr>
<tr>
<td>Nitrite, N-NO₂</td>
<td>mg/L</td>
<td>0.14</td>
<td>0.07</td>
<td>0.02</td>
<td>2.64</td>
<td>0.02</td>
</tr>
<tr>
<td>Iron, Fe²⁺</td>
<td>mg/L</td>
<td>3.00</td>
<td>0.15</td>
<td>&lt;0.01</td>
<td>1.00</td>
<td>0.99</td>
</tr>
<tr>
<td>Phosphate, PO₄³⁻</td>
<td>mg/L</td>
<td>3.3</td>
<td>1.4</td>
<td>7.8</td>
<td>10.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Sulphate, SO₄²⁻</td>
<td>mg/L</td>
<td>43</td>
<td>&lt;1</td>
<td>102</td>
<td>&lt;1</td>
<td>39</td>
</tr>
<tr>
<td>Fluoride, F⁻</td>
<td>mg/L</td>
<td>0.045</td>
<td>0.041</td>
<td>0.738</td>
<td>0.762</td>
<td>0.271</td>
</tr>
</tbody>
</table>

4.3 Coagulant dosing

The residual turbidity decreases to a certain dosage of natural coagulants, which is referred to as the optimized dose. Dosages above the optimum results in increased turbidity, why it is important not to overdose the natural coagulants. Alum does not show theses properties; the turbidity decreases to a certain level and does not decrease more with a higher dosage. See diagrams in figure 5.

4.4 Turbidity removal

The percental increase in removal of turbidity show the difference between the reference beaker and the beaker with the optimum dosage of natural coagulants or alum. Residual turbidities, dosage and standard deviations (where the number of tests allow it) are also given in the tables, see tables 3-9. The results shown give the lowest obtained residual turbidity and dosage.

4.4.1 Surface water

Acceptable turbidity values for drinking water of 5 NTU (WHO, 2008) and below was obtained for all coagulants at initial turbidity of 400 NTU in surface water. Required dosages of coagulants ranged between 0.4 - 1.6 mL coagulant solution in 500 mL samples of river water. Defatted seeds needed a higher dosage and provided better final results than the undefatted seeds, with the exception of tests with defatted Vigna unguiculata (dCSE C) on surface water with 2000 NTU. The dCSE C solution reached a residual turbidity of 25 NTU. It was discovered that the seed solution was 12 days old and were probably too old to provide a fair result. Pictures of the reference beaker and the beaker with the
Figure 5: Surface water, 400 NTU: Residual turbidity and dosages of coagulants. Note the trend in increasing turbidity with increased dosage of natural coagulants.
Enhancing the capacity of seds to remove turbidity in water treatment

Figure 6: Surface water, 400 NTU: Residual turbidity after coagulation and flocculation with CSE P. Left: Reference beaker, 314 NTU. Right: 0.5 mL CSE P dosed, 3 NTU.

An optimized dose of defatted *Parkinsonia aculeata* seeds are shown in figure 6.

The standard deviations for the tests on surface water with initial turbidity of 400 NTU are 6.2 for CSE C, 6.4 for dCSE C, 13.2 for CSE P, 2.1 for dCSE P and 20.6 for alum. The standard deviations are based on at least three tests with the same dosage. Removal efficiencies and standard deviations are given in tables 3-6. Tables comparing the residual turbidities for each coagulant are presented in Appendix II.

### Table 3: Surface water, initial turbidity 250 NTU: Turbidity removal of natural coagulants.

<table>
<thead>
<tr>
<th>Coagulant</th>
<th>Optimized dosage [mL]</th>
<th>Residual turbidity [NTU]</th>
<th>Increased removal [%]</th>
<th>no of tests</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSE C</td>
<td>0.5</td>
<td>10</td>
<td>73</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>dCSE C</td>
<td>1</td>
<td>5</td>
<td>86</td>
<td>4</td>
<td>2.1</td>
</tr>
<tr>
<td>CSE P</td>
<td>0.4</td>
<td>4</td>
<td>78</td>
<td>3</td>
<td>13.2</td>
</tr>
<tr>
<td>dCSE P</td>
<td>0.5</td>
<td>2</td>
<td>82</td>
<td>3</td>
<td>10.7</td>
</tr>
</tbody>
</table>

### Table 4: Surface water, initial turbidity 400 NTU: Turbidity removal of coagulants.

<table>
<thead>
<tr>
<th>Coagulant</th>
<th>Optimized dosage [mL]</th>
<th>Residual turbidity [NTU]</th>
<th>Increased removal [%]</th>
<th>no of tests</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSE C</td>
<td>0.9</td>
<td>5</td>
<td>67</td>
<td>5</td>
<td>6.2</td>
</tr>
<tr>
<td>dCSE C</td>
<td>1.6</td>
<td>4</td>
<td>69</td>
<td>6</td>
<td>6.4</td>
</tr>
<tr>
<td>CSE P</td>
<td>0.5</td>
<td>3</td>
<td>77</td>
<td>3</td>
<td>13.2</td>
</tr>
<tr>
<td>dCSE P</td>
<td>0.6</td>
<td>2</td>
<td>58</td>
<td>3</td>
<td>2.1</td>
</tr>
<tr>
<td>Alum</td>
<td>0.5</td>
<td>4</td>
<td>74</td>
<td>6</td>
<td>20.6</td>
</tr>
</tbody>
</table>
Table 5: Surface water, initial turbidity 750 NTU: Turbidity removal of natural coagulants.

<table>
<thead>
<tr>
<th>Coagulant</th>
<th>Optimized dosage [mL]</th>
<th>Residual turbidity [NTU]</th>
<th>Increased turbidity removal [%]</th>
<th>no of tests</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSE C</td>
<td>2</td>
<td>8</td>
<td>77</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>dCSE C</td>
<td>2</td>
<td>1</td>
<td>69</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>CSE P</td>
<td>1</td>
<td>14</td>
<td>72</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>dCSE P</td>
<td>2</td>
<td>1</td>
<td>80</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6: Surface water, initial turbidity 2000 NTU: Turbidity removal of coagulants.

<table>
<thead>
<tr>
<th>Coagulant</th>
<th>Optimized dosage [mL]</th>
<th>Residual turbidity [NTU]</th>
<th>Increased turbidity removal [%]</th>
<th>no of tests</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSE C</td>
<td>6</td>
<td>5</td>
<td>78</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>dCSE C</td>
<td>6</td>
<td>25</td>
<td>74</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>CSE P</td>
<td>1</td>
<td>14</td>
<td>72</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>dCSE P</td>
<td>6</td>
<td>1</td>
<td>61</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Alum</td>
<td>7</td>
<td>5</td>
<td>53</td>
<td>2</td>
<td>-</td>
</tr>
</tbody>
</table>

4.4.2 Synthetic turbid water

Tests on synthetic turbid water focused on turbidities of 400 NTU. Tests on other turbidities provide an idea of the efficiencies of the coagulants on other turbidities.

The natural coagulants did have some effect on turbidity removal, but the results are uneven and far from adequate with residual turbidities of 31 NTU at the lowest (CSE C on water with initial turbidity of 400 NTU) and 707 NTU at the highest, which was a higher turbidity than the reference beaker (dCSE C on water with initial turbidity of 750 NTU), see tables 7-9. The standard deviations were 81.5 for CSE C and 8.5 for CSE P on an initial turbidity of 400 NTU. A table comparing the residual turbidities for the coagulants is presented in Appendix II.

Table 7: Synthetic turbid water, initial turbidity 250 NTU: Turbidity removal of coagulants.

<table>
<thead>
<tr>
<th>Coagulant</th>
<th>Optimized dosage [mL]</th>
<th>Residual turbidity [NTU]</th>
<th>Increased turbidity removal [%]</th>
<th>no of tests</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSE C</td>
<td>4</td>
<td>56</td>
<td>72</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>dCSE C</td>
<td>0.5</td>
<td>154</td>
<td>37</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>CSE P</td>
<td>1</td>
<td>233</td>
<td>6</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>
4.4.3 Waste water

Seed solutions of undefatted *Vigna unguiculata* and *Parkisonia aculeata* were tested on wastewater. Defatted seed solutions were unfortunately not tested due to limitations of time and resources.

The effect on turbidity removal of the undefatted seed solutions was not adequate, with increased turbidity removals of 13 % and 3 % for Vigna unguiculata (CSE C) and *Parkisonia aculeata* (CSE P), respectively. Alum had a turbidity removal of almost 60 % and was the only coagulant with effect on the turbidity-removal in the tests. One test on each coagulant was made, adding 0, 0.5, 1, 2, 3, 4 mL 1 % w/W seed solution to each beaker. Results are presented in table 10.

4.5 Fluoride removal

The initial concentration of fluoride in the water was 8.71 mg/L. The coagulants were dosed adding 0, 0.5, 1, 2, 3, 4 mL of the seed solutions to the six beakers in the jar-test set up, with one test for each coagulant. None of the seed solutions performed adequately in reducing the concentrations of fluoride. There was a slight decrease

---

**Table 8: Synthetic turbid water, 400 NTU: Results on turbidity removal from all coagulants.**

<table>
<thead>
<tr>
<th>Coagulant</th>
<th>Optimized dosage [mL]</th>
<th>Residual turbidity [NTU]</th>
<th>Increased removal [%]</th>
<th>no of tests</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSE C</td>
<td>0.5</td>
<td>31</td>
<td>45</td>
<td>3</td>
<td>81.5</td>
</tr>
<tr>
<td>dCSE C</td>
<td>0.5</td>
<td>371</td>
<td>4.5</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>CSE P</td>
<td>0.5</td>
<td>104</td>
<td>74</td>
<td>4</td>
<td>8.5</td>
</tr>
<tr>
<td>dCSE P</td>
<td>0.5</td>
<td>159</td>
<td>43</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>Alum</td>
<td>1</td>
<td>24</td>
<td>88</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 9: Synthetic turbid water, 750 NTU: Results for turbidity removal.**

<table>
<thead>
<tr>
<th>Coagulant</th>
<th>Optimized dosage [mL]</th>
<th>Residual turbidity [NTU]</th>
<th>Increased removal [%]</th>
<th>no of tests</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>dCSE C</td>
<td>3</td>
<td>707</td>
<td>-0.4</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>CSE P</td>
<td>0.5</td>
<td>659</td>
<td>6</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Alum</td>
<td>0.5</td>
<td>12</td>
<td>85</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 10: Waste water: Results on turbidity removal.**

<table>
<thead>
<tr>
<th>Coagulant</th>
<th>Optimized dosage [mL]</th>
<th>Initial turbidity [NTU]</th>
<th>Residual turbidity [NTU]</th>
<th>Increased removal [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSE C</td>
<td>0.5</td>
<td>122</td>
<td>106</td>
<td>13</td>
</tr>
<tr>
<td>CSE P</td>
<td>0.5</td>
<td>278</td>
<td>113</td>
<td>3</td>
</tr>
<tr>
<td>Alum</td>
<td>4</td>
<td>118</td>
<td>19</td>
<td>59</td>
</tr>
</tbody>
</table>
Table 11: Water from a drilled well, initial fluoride concentration 8.71 mg/L: Results on fluoride concentrations.

<table>
<thead>
<tr>
<th>Coagulant</th>
<th>dosage [mL]</th>
<th>Residual, F&lt;sup&gt;-&lt;/sup&gt; [mg/L]</th>
<th>Increased removal [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSE C</td>
<td>0.5</td>
<td>6.62</td>
<td>7</td>
</tr>
<tr>
<td>dCSE C</td>
<td>1</td>
<td>7.41</td>
<td>6</td>
</tr>
<tr>
<td>CSE P</td>
<td>1</td>
<td>6.68</td>
<td>8</td>
</tr>
<tr>
<td>dCSE P</td>
<td>4</td>
<td>8.32</td>
<td>4</td>
</tr>
<tr>
<td>alum</td>
<td>2</td>
<td>7.14</td>
<td></td>
</tr>
</tbody>
</table>

of fluoride concentrations with a higher dosage of coagulants, with an increased percental removal ranging between 4 % and 8 %. The final fluoride concentrations were at the lowest 6.62 mg/l (CSE C) and 8.32 mg/L (dCSE P), see table 11.

4.6 Coagulant aids

4.6.1 Surface water

Surface water with initial turbidity of 2000 NTU was tested with alum as primary coagulant and natural coagulants as coagulant aids. Half the optimized dose in surface water with 2000 NTU was chosen for alum, 3.5 mL, in each beaker (optimized dose in table 6. All natural coagulants managed to reach acceptable residual turbidities, except defattened seeds of *Vigna unguiculata* (dCSE C). dCSE C reached a lowest residual turbidity of 8 NTU, see table 12. This is 3 NTU above acceptable limit (WHO, 2008). One test was made for each seed solution. Sludge volumes produced were also measured, see section 4.8 Sludge.

The results from the tests with coagulant aids on surface water show that undefattened and defattened seeds of *Parkinsonia aculeata* can improve the final result in turbidity removal acting as a coagulant aid with alum. Tests with undefattened *Vigna unguiculata* as a coagulant aid reached the same turbidity values as alum alone does. The defattened seeds of *Vigna unguiculata* came close to the turbidity levels that alum is capable of, but did not reach lower values.

Table 12: Surface water, initial turbidity 2000 NTU: 3.5 mL of Alum with optimized dosages of natural coagulants as coagulant aids.

<table>
<thead>
<tr>
<th>Coagulant aid</th>
<th>Optimized dosage [mL]</th>
<th>Residual turbidity [NTU]</th>
<th>Increased removal [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSE C</td>
<td>5</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>dCSE C</td>
<td>5</td>
<td>8</td>
<td>100</td>
</tr>
<tr>
<td>CSE P</td>
<td>5</td>
<td>1</td>
<td>24</td>
</tr>
<tr>
<td>dCSE P</td>
<td>4.5</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>alum only</td>
<td>7</td>
<td>5</td>
<td>53</td>
</tr>
</tbody>
</table>
4.6.2 Waste water

One seed solution was tested as coagulant aid with alum in waste water; undefatted seeds of *Vigna unguiculata*. Half the optimized dose of alum in waste water, 2 mL, was added to the beakers before the test (the optimized dose is found in table 10). The best obtained result with *Vigna unguiculata* as coagulant aid was a residual turbidity of 32 NTU which represents an increased removal of 9.32 % compared to the reference beaker. There was no trend in behaviour on residual turbidity with the dosage of seed solution. Alum showed a removal efficiency of 59 % (with a residual turbidity of 19 NTU). The turbidity-dosage curve for alum and *Vigna unguiculata* is presented in figures 7 and 8.

![Figure 7: Waste water, initial turbidity 118 NTU: Residual turbidity and dosage of alum.](image)

![Figure 8: Waste water, initial turbidity 118 NTU: Residual turbidity and dosage of undefatted *Vigna unguiculata* (CSE C) as coagulant aid to 2 mL of alum. Note: It is not possible to distinguish any effect of the coagulant aid at this dosage of alum.](image)
4.7 Dependence of pH

None of the coagulants functioned better with lower pH-values of 5 and 6 in surface water. CSE C was least affected by the pH change with a residual turbidity of 21 NTU for pH 5.2 and 10 NTU for pH 8.2. All other coagulants, including alum, had reduced efficiency with lower pH-values, see diagram in figure 9. Natural pH of the surface water ranged between 7.5 and 8.2. One test set-up was made for each seed solution with the lower pH-values.

Tests on lower pH was also conducted on water with high concentrations of fluoride to see if the effect on fluoride removal changed with a different pH. The test results did however not show any effect at all in removal of fluoride.

4.8 Water parameters

The measured parameters of the water samples are given in table 13. The big differences in quality of the different water samples are the electric conductivity, TDS and alkalinity, the highest values belonging to the water from the drilled well with 1119 µS/cm and 559 mg/L respectively. The waste water differed significantly between the two different dates of collection, especially the electric conductivity, TDS and salinity.
Table 13: Water parameters for collected surface water from Ruvu juu, waste water from Ardhi University and groundwater from a drilled well with high levels of fluoride.

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
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<tr>
<td>pH</td>
<td></td>
<td>7.98</td>
<td>7.95</td>
<td>7.89</td>
<td>7.27</td>
<td>7.49</td>
<td>8.29</td>
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<tr>
<td>Temperature</td>
<td>°C</td>
<td>15.9</td>
<td>28.6</td>
<td>26.5</td>
<td>25.0</td>
<td>24.3</td>
<td>22.5</td>
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<tr>
<td>Electric conductivity</td>
<td>µS/cm</td>
<td>167</td>
<td>176</td>
<td>236</td>
<td>25</td>
<td>744</td>
<td>1119</td>
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<tr>
<td>TDS</td>
<td>mg/L</td>
<td>83</td>
<td>88</td>
<td>118</td>
<td>13</td>
<td>372</td>
<td>559</td>
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<tr>
<td>Salinity</td>
<td>%</td>
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<td>0.1</td>
<td>0.1</td>
<td>15.3</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Phenol</td>
<td>mg/L</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>mg/L</td>
<td>93</td>
<td>90</td>
<td>218</td>
<td>555</td>
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<td></td>
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<tr>
<td>Hardness, Ca²⁺</td>
<td>mg/L</td>
<td>62</td>
<td>75</td>
<td>21</td>
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<td></td>
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<tr>
<td>Total hardness, Ca²⁺ Mg²⁺</td>
<td>mg/L</td>
<td>100</td>
<td>132</td>
<td>275</td>
<td>25</td>
<td></td>
<td></td>
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<tr>
<td>Chloride, Cl⁻</td>
<td>mg/L</td>
<td>54</td>
<td>87</td>
<td>42</td>
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<td></td>
<td></td>
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<tr>
<td>COD</td>
<td>mg/L</td>
<td>53</td>
<td>119</td>
<td>262</td>
<td>63</td>
<td></td>
<td></td>
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<tr>
<td>Nitrite, NO-N₂</td>
<td>mg/L</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
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<td>0.03</td>
<td>0.01</td>
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<tr>
<td>Iron, Fe²⁺</td>
<td>mg/L</td>
<td>1.12</td>
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<td>0.07</td>
<td>0.08</td>
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<tr>
<td>Phosphate, PO₄³⁻</td>
<td>mg/L</td>
<td>0.5</td>
<td>1.1</td>
<td>4.0</td>
<td>5.2</td>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>Sulphate, SO₄²⁻</td>
<td>mg/L</td>
<td>13</td>
<td>9</td>
<td>7</td>
<td>8</td>
<td></td>
<td>41</td>
</tr>
<tr>
<td>Fluoride, F⁻</td>
<td>mg/L</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.71</td>
</tr>
</tbody>
</table>

4.9 Sludge

A distinct sludge phase and clear water phase had developed after 30 minutes and the sludge volumes decreased the following 30 minutes, when the sludge had been allowed to pack.

Undefattened seed solutions of Vigna unguiculata and Parkinsonia aculeata produced 2.5 times less sludge volumes compared to alum after 60 minutes settling time of treated surface water with initial turbidity of 400 NTU. Defattened seeds of Vigna unguiculata produced 1.7 times less sludge than alum. Defattened seeds of Parkinsonia aculeata produced a little more sludge than alum. The produced sludge volumes for the treated surface water with initial turbidity of 400 NTU are shown in figure 10. Residual turbidities in the clarified water ranged between 0-16 NTU. One test on each coagulant was made.

Sludge volumes were also measured on surface water treated with alum and coagulant aids. The initial turbidity was 2000 NTU. The volume of sludge produced by all reference beakers is used to calculate an average reference value. 3.5 mL of alum was dosed in each beaker including reference beaker (3.5 mL is half the optimized dose of alum, see table 6).
Undefattened and defattened seeds of *Vigna unguiculata* produced 1.8 times and 1.6 times more sludge than the average reference beaker, respectively. Both types of seeds from *Parkinsonia aculeata* produced 2 times more sludge than the reference beaker. However, the average reference beaker had 580 NTU as residual turbidity, while the residual turbidities of the seeds ranged between 1-8 NTU. Unfortunately no comparing experiment measuring sludge was made for alum without coagulant aids.

See figure 11 for values on sludge volumes produced when testing seed solutions as coagulant aids.

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**Figure 10:** Surface water, 400 NTU: Sludge volumes produced after coagulation-flocculation after 30 minutes and 60 minutes. Residual turbidities in NTU.

**Figure 11:** Surface water, 2000 NTU: Sludge volumes produced after coagulation-flocculation. 3.5 mL alum dosed in each beaker as primary coagulant. “Ref.” represent the average values of each reference beaker in the jar-tests.
5 DISCUSSION

The natural coagulants are effective in reducing the turbidity of surface water and can compete with alum in water treatment purposes.

The acceptable turbidity limit for drinking water is 5 NTU, according to the World Health Organization (WHO, 2008). The same value is used by TBS, Tanzania Bureau of Standards (TBS, 1999). Undefatted seeds clarified surface water to 3-4 NTU for initial turbidities of 250 and 400 NTU in surface water. They did not perform turbidities within acceptable limits for drinking water on the higher initial turbidities (750 and 2000 NTU). Defatted seeds of Parkinsonia aculeata clarified surface water of all tested turbidities in surface water to final values of 1-2 NTU, reaching lower residual turbidities for all tested turbidities than the undefatted seeds did. The increased percentage of turbidity removal on all turbidities in surface waters ranged between 72-78 % for undefatted seeds and 58-80 % for the defatted seeds of Parkinsonia aculeata.

Undefatted seeds of Vigna unguiculata managed to clarify surface water to 5 NTU on water with initial turbidities of 250 and 2000 NTU. They did not perform as well in surface waters with initial turbidity of 400 and 750 NTU. Defatted Vigna unguiculata seeds clarified surface water to 1-5 NTU for surface water with initial turbidities of 250-750 NTU. They did not reach acceptable limits for the highest tested initial turbidity (2000 NTU). The increased percentage removal ranged between 67-78 % for undefatted seeds and 69-86 % for defatted seeds of Vigna unguiculata.

Generally, it seems as if the defatted seeds are able to reach lower residual turbidities in treated surface water than the undefatted seeds. It is however questionable to use alcohol as a defattening agent in preparation of coagulant agents used in water treatment, since the manufacturing of alcohol itself depend on access to clean water.

The defatted seeds of Parkinsonia aculeata clarified the surface water samples to the lowest values on all tested turbidities on surface water, compared to all other coagulants. This could mean that these seeds could be used in water treatment plants to reach better final turbidities than alum alone would.

The defatted seeds did not show better clarifying properties on synthetic turbid water than the undefatted seeds. Actually, none of the tested coagulants reached acceptable limits for turbidity in drinking water. An attempt to explain this behaviour of the coagulants is if the water samples did not provide enough organic material to bind to, to start the coagulating reaction. If that would be the case, the seeds would start the coagulating reaction, creating nuclei necessary for the agglomeration of all sorts of particles in the floculation. This is however not a complete answer, since one of the problems in water treatment with natural coagulants is thought to be the addition of organic material to the treated water.
Waste water was tested to provide experiments on water with higher organic contents. Alum showed clarifying properties, with an increased percentual turbidity removal of 59%. Undefattened seeds of *Vigna unguiculata* and *Parkinsonia aculeata* and alum was tested but did not show any clarifying effect on the waste water. This is contradictory to the idea that the organic content would be the limiting factor in the coagulating reaction. The organic content could however not only provide a limiting factor, but also an inhibiting factor if the concentrations are too high. Studies on Swiss hard water lakes has shown that two important factors affect the stability of particles in lakes; calcium and organic matter. Calcium ions destabilize colloidal particles while organic matter stabilizes colloidal particles (Stumm and Morgan, 1996). No tests have been made so far testing if the seeds have an optimum functionality with a certain concentration of organic material in the water. The dosage-turbidity relationship of the natural coagulants may be part of the answer to this question. The residual turbidity after coagulation and flocculation decreases to a certain dosage of seed solution and then start to increase with increasing dose. Defattening of the seeds reduced this property of an increasing turbidity with a higher dosage, providing a method that is less sensitive to unprecise dosage.

A study on purification of the coagulant protein from *Moringa oleifera* seed by single-step ion exchange (Ghebremichael et al, 2006) managed to reduce COD-values of 12 000 mg/L to 96 % after purification. The COD of the natural coagulants were reduced by 10.7-11.5 % of the original COD values in this study. Defattening of the seeds did not result in higher concentrations of proteins in the seed solutions, but it lowered the total hardness, electric conductivity, totally dissolved solids and COD of the coagulant solutions. Other methods than defattening should be tested to achieve low hardness and COD-values in a low-tech manner.

None of the coagulant solutions had adequate effect on removal of fluoride after coagulation and flocculation. The acceptable limit of fluoride concentration in drinking water is 1.5 mg/L, according to WHO (2008) and TBS (1999). None of the coagulants came close to the acceptable limits. The increased percentage removal of fluoride by the seeds were 4-8 %. Only one test was made with each coagulant, why the results are not statistically verified, but they indicate the seeds are improper to use for fluoride removal. None of the known methods on defluoridation imply that a defluoridation with *Vigna unguiculata* and *Parkinsonia aculeata* should be expected. Tests with Nirmali seeds for fluoride removal in water has been made earlier (Srimurali et al, 1998), with similar results as the seeds of *Vigna unguiculata* and *Parkinsonia aculeata* with fluoride removal of 6-8 %. More knowledge on functional groups of *Vigna unguiculata* and *Parkinsonia aculeata* should be sought after to evaluate the properties and possible usages of these seeds.

The natural coagulants were tested as coagulant aids with the widely used chemical coagulant alum. They were tested together.
to evaluate if a large scale usage of natural coagulants would be possible in existing water treatment technology. Seeds of *Parkinsonia aculeata* lowered the residual turbidity below the values alum is capable of. Seeds of *Vigna unguiculata* did not perform lower turbidities than alum. The undefatted seeds are preferable as coagulant aids to alum over defatted seeds, because they perform the lowest residual turbidities. This study show that it could be possible to use natural coagulants in combination with alum, but the tests have only been performed in jar-tests and should be tested in large scale to investigate the behaviour of the seeds with large amounts of water.

Low pH-values affect the clarifying capacity of the coagulants. Defattened seeds of *Vigna unguiculata* and both types of seed solutions of *Parkinsonia aculeata* had reduced capacities in turbidity removal at pH 5. The undefattened seeds of *Vigna unguiculata* were least affected by the reduction of pH. This could be an important knowledge in creating the best conditions for the natural coagulants to function in water treatment, especially for treatment of different types of water. It is also an interesting observation that might imply that the seeds of *Vigna unguiculata* could be the most suitable seed to use as a coagulant aid with alum, since alum has a low pH of 3.6.

The experiments also showed that natural coagulants reduced the sludge volumes produced when using natural coagulants together with alum. This is beneficial since large sludge volumes are difficult and expensive to handle.

Antimicrobial studies has shown that purified proteins of *Parkinsonia aculeata* and *Vigna unguiculata* show properties of flocculation, aggregation and inhibition of the growth of bacterial cells. The mechanisms responsible for the antibacterial properties are believed to involve peptides that perforate bacterial cell membranes or inhibit essential enzymes in the bacteria. Bacterial flocculation is also involved in the antimicrobial effects (Marobhe et al, 2008b). The question is if the removal of bacteria is enough and how long time the water may be stored before consumption.

The price of treating water is an important factor in a world where the principle of free water still lives. Alum is estimated to cost approximately 0.1 USD/kg (100 USD/ton) (Guangzhou ZeRon Chemical Technology Co. Ltd., 2011). 1 kg of *Vigna unguiculata* costed approximately 0.7 USD at Magomeni market in Dar es Salaam in october 2010. The used amounts of natural coagulants has in this study been the same or larger than the amount alum used. The price of the natural coagulants is a great obstacle in competition with alum, as long as the costs of handling alum are low. However, it might be possible to lower the cost of the seeds if the production of *Vigna unguiculata* and *Parkinsonia aculeata* could be industrialized. If the total price would be considered, with life cycle calculations, the issues concerning sludge handling is an important advantage speaking for the natural coagulants. Reduced sludge volumes is one advantage, another benefit is that the sludge
produced by the natural coagulants may be spread on arable land, where the used resources and nutrients can be recycled. The natural coagulants also have an advantage in rural areas since they often are locally available. This is in comparison to alum that has to be shipped from alum manufacturing countries.

5.1 Areas of further interest

• The change of effect in turbidity removal of the natural coagulants depending on pH in the treated water should be investigated and explained.

• Optimization of the organic content in treated water for an optimal functionality of the seeds would contribute with knowledge on how to best treat water of different origins.

• Other purification methods should be tested to remove organic content from the seed solutions.

• Does the properties of alum change when the natural coagulants are used as coagulant aids?

• Is the treatment of water with natural coagulants in drinking water enough regarding bacteria, virus and other pollutants?
REFERENCES


OTHER REFERENCES


Interview with Mr Ramadhani Mbulumbe, labassistant at Ardhi University. 15 November 2010.

APPENDIX I

Interview with Mr Ramadhani Mbulumbe, laboratory assistant at Ardhi University. 15 November 2010, on *Vigna unguiculata*:

“The seeds are grinded and used directly as they are by dosing the coagulants as powder to buckets of water. 1 teaspoon seed powder is added to a bucket of 20 litres, followed by rapid mixing and slow mixing by hand. The water is sometimes treated with ash to rise the pH, but it isn’t preferrable to serve drinking water with high pH-values. Some of the seeds used in the villages react with the treated water during storage, makin it smell bad after a day or two.

Choroko can be boiled with ash to reduce the cooking time to 45 minutes to 1 hour, the beans have to boil for approximately 2 hours without ash. Choroko is harvested in june to august and cost 1000 - 2000 TSh/kg (1000 TSh = 4,2 SEK = 0,5 EUR ). One family use approximately 1 kg choroko each year. Choroko is grown in clay or silty soil. The plant rests from the harvest is used as fodder to the cows. Rama estimates the water supply for one plant to 0,5 L/day. Choroko takes 3 days to germinate. It grows for 3 months prior to harvest. Choroko reaches a hight of approximately 2 dm.

Issues regarding water supply in rural villages; the water is collected from ponds, wells etc. during the dry season (august to december). River water is used during the wet season. There is also a problem of functioning pumps in these areas. Singida have several salt ponds (no mining).

You can find choroko in Singida, Iringa, Morogoro and Mbeya. Parkinsonia is only found in Singida (plus two known places in Dar es Salaam).”
## APPENDIX II

**Tables comparing results in turbidity removal**

*Surface water: Residual turbidities of the optimized dosages compared. Initial turbidities are 250, 400, 750 and 2000 NTU.*

<table>
<thead>
<tr>
<th>Coagulant</th>
<th>250 NTU</th>
<th>400 NTU</th>
<th>750 NTU</th>
<th>2000 NTU</th>
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<td>CSE C</td>
<td>10</td>
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<td>8</td>
<td>5</td>
</tr>
<tr>
<td>dCSE C</td>
<td>5</td>
<td>4</td>
<td>1</td>
<td>25</td>
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<tr>
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<td>1</td>
</tr>
<tr>
<td>Alum</td>
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<td>4</td>
<td>5</td>
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</tbody>
</table>

*Synthetic turbid water: Residual turbidities of the optimized dosages compared. Initial turbidities are 250, 400 and 750 NTU.*

<table>
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<td>Alum</td>
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<td>12</td>
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Appendix III

Specified list of laboratory equipment

Spectrophotometer  model HACH DR/2010, Portable Datalogging Spectrophotometer. Programme #750 measuring FAU at 860 nm.
Fluoride Electrode  model HACH SensIon2 51928 Platinum Series

HACH Bufferpillows used

Fluoride, F^-  Fluoride Adjustment Buffer Powder Pillows cat. 2589-99
Iron, Fe^{2+}  FerroVer Iron Reagent
Nitrite, N-NO_2  NitriVer3 Nitrite Reagent
Phosphate, PO_4^{3-}  PhosVer3 Phosphate Reagent
Sulfate, SO_4^{2-}  SulfaVer4 Sulfate Reagent
Total hardness  ManVer2 Hardness Indicator