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Experiment 2: Treatment of Turbid Water Using Moringa Oleifera

da Silva, X
Maré, DC
Kgwadi, R

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Xandro da Silva
15006931

Dewald Maré
16117418

Remoakantse Kgwadi
17129053

Department of Chemical Engineering
University of Pretoria
South Africa

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Abstract

Moringa, $FeCl_3$ and 50:50 $FeCl_3$-Moringa were used as coagulants to study the behaviour of Kaolin clay in water. This was done by conducting batch-settling tests using different dosages of each coagulant. A sedimentation tank was designed to treat 50 Ml/(day) of an inlet stream that contained 2.5 $\mathrm{g\,l^{-1}}$ of colloidal suspension.

The optimal dosage of $FeCl_3$ runs was found to be 3 g $FeCl_3$ because it produced the lowest turbidity of 223 NTU. 5 g Moringa was the optimal dosage for the Moringa runs with a turbidity of 108 NTU. $FeCl_3$-Moringa 50:50 combination was found to produce unsatisfactory results as a clear interface layer (during the batch-settling tests) were not seen. For the sedimentation tank design, using the optimal coagulant dosages, a cross-sectional area of 38748 m^2 for the 3 g $FeCl_3$ and 6831 m^2 for the 5 g Moringa were calculated.

It is recommended to have a large amount of Moringa and $FeCl_3$ should be provided to allow for repeatability and to conduct more batch-settling tests at different dosages. Also, it is recommended to use image comparison software to clearly see the interface layer for the $FeCl_3$-Moringa combination.

Keywords: Moringa Oleifera, $FeCl_3$, Coagulation, Sedimentation.

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Nomenclature

A	Cross-sectional area of vessel	m^2
A_{min}	Minimum cross-sectional area.	m^2
C_0	Initial concentration at the interface height	$kg\,m^{-3}$
c_f	Concentration of feed stream.	$kg\,m^{-3}$
C_i	Concentration at the specific interface height	$kg\,m^{-3}$
c_o	Concentration of overflow stream.	$kg\,m^{-3}$
c_u	Concentration of underflow stream.	$kg\,m^{-3}$
$G_{max,s}$	Maximum settling flux.	$kg\,s^{-1}\,m^{-2}$
G_s	Settling flux.	$kg\,s^{-1}\,m^{-2}$
h_0	Initial interface height	m
h_i	Interface height at a certain time i.	m
Q_f	Volumetric flow rate of feed.	$m^3\,s^{-1}$
Q_o	Volumetric flow rate of overflow.	$m^3\,s^{-1}$
Q_u	Volumetric flow rate of underflow.	$m^3\,s^{-1}$
t	Time	s
u_H	Hindered settling velocity.	$m\,s^{-1}$
u_s	Hindered settling velocity at specific interface height i.	$m\,s^{-1}$

1 Introduction

1.1 Background

With surging population growth and rapid industrial development in urban centres, water sanitation has become an increasingly global priority according to Choy *et al* (2014). It is essential to treat fresh water supplies from contaminants and colloidal material that are potentially harmful for human consumption. Turbidity is a general measure of how opaque or cloudy the water is and is a good indicator of water quality. Turbidity is attributed to suspended colloidal matter in the water. According to WHO (2017), drinking water should be no more than 5 NTU (nephelometric turbidity unit) and should ideally be below 1 NTU. The process of coagulation is often employed in the reduction of turbidity of drinking water.

Coagulation is a physical-chemical process that makes use of chemical coagulants such as alum ($AlCl_3$), ferric chloride ($FeCl_3$) and synthetic polymers (polyamine) to remove the turbidity of water (Maurya & Daverey, 2018). Although chemical coagulants are effective and commonly used in water treatment, they are not sustainable and pose a potential health threat since it is not bio-degradable. An alternative, more sustainable option is to use natural plant-based coagulants. According to Maurya & Daverey (2018), natural coagulants are more advantageous than their chemical counterparts. They are bio-degradable, cheaper than chemical coagulants, non-toxic and non-corrosive. Also since it produces less sludge, as compared to chemical coagulants, the sludge handling and disposal are cheaper. However, natural coagulants have yet to be commercialised due to challenges in harvesting and processing natural coagulants from plants.

1.2 Problem Statement and Objectives

A company wants to investigate and design an "Environmentally friendly water treatment plant". In order to achieve this, it has been proposed to switch from using chemical coagulants to natural coagulants. Moringa Oleifera, a plant that originates from Asia, will be used as coagulant for treatment of turbid water and possibly minimize or eradicate the use of conventional chemical coagulants. Due to the Covid-19 pandemic access to the company's laboratory and facilities are prohibited and is cause of great hindrance to this project. However, samples of the material found in the suspensions, Moringa powder, $FeCl_3$ and a few other items were provided to conduct experimental work at home.

The main objective is to investigate the sedimentation behaviour of Kaolin powder using Moringa seed powder, $FeCl_3$ and 50:50 Moringa-$FeCl_3$ combination as coagulants, this is to be conducted by doing several batch settling tests. $FeCl_3$ coagulant will be used as the baseline experiment to which all other experimental results will be compared too. In addition, different dosages of the coagulants will be conducted to determine the optimal dosage and its hindered velocity. The sedimentation behaviour of Kaolin powder of the different coagulants will be compared by how much is required to treat the turbid water and the turbidity of the water

Using the determined optimal dosage and its hindered velocity for each coagulant, a sedimentation tank is to be designed to determine the feasibility of each coagulant. The most important design parameter of the tank is the cross-sectional surface area of each tank. The sedimentation tank must take an inlet stream of 50 Ml/(day) of colloidal suspension concentration of 50 g l^{-1}.

1.3 Method and Scope

This report will discuss the water treatment process to treat turbid water; looking closely at coagulation and sedimentation. Furthermore, experiments will be done to study sedimentation behaviour of Kaolin powder using Moringa seed powder and $FeCl_3$ as coagulants. The results from the experiments will be presented and discussed. Finally, conclusions of these results will be made and recommendations will be prescribed to improve this study or ways to achieve better results.

2 Theory

2.1 Water Treatment Process

According to Britannica (2020), water sources such as rivers or lakes are not safe enough for human consumption and require water treatment. Even ground water sources, which are much cleaner than other water sources, require water treatment. The main goal of water treatment is to provide safe-drinking water, free of harmful microorganisms and chemicals. Moreover, public supplies require water to be ascetically pleasing to its consumers as well. Factors such as the colour (water should be crystal clear), odour and taste of the water need to be taken into account in the water treatment process. According to CDC (2015), surface water typically requires more treatment and filtration than ground water sources because they contain more colloidal suspension and are more likely to be contaminated with pollutants.

According to the CDC (2015), coagulation and flocculation are typically the first steps in the water treatment process. Smaller-suspended particles that are too light to settle on its own cannot be removed completely by discrete settling (Britannica, 2020). As a result of this, a chemical coagulant is added to bring non-settling particles together into heavier particles called floc and help facilitate sedimentation. More in-depth analysis on the coagulation and flocculation process will be discussed below.

The steps that proceeds after coagulation and flocculation are sedimentation and filtration (CDC, 2015). During the sedimentation process, the floc settles to the bottom of the tank while the clear water flows out in the overflow stream to the next step (filtration). According to Britannica (2020), the efficiency of a sedimentation tank in removing sediments depends more on the tank's surface area rather than its volume or depth. However, most modern day sedimentation tanks are not less than 3 metre deep because enough room must be provided for the sludge layer to form and scraper machine to operate.

Filtration proceeds after the sedimentation process. Even after the sedimentation process, filtration is required to remove the smallest of particulate-suspended matter and non-settled floc (SDWF, 2017a). A conventional filtration system typically consists of filters with varying sizes of porous media, and are often made up of sand, gravel and charcoal. Filtration is absolutely essential to make the water crystal clear and remove any of the remaining suspended particles that could have bacteria attached onto them (Britannica, 2020).

There are two basic types of sand filtration; slow sand filtration and rapid sand filtration (SDWF, 2017a). Slow sand filtration is a biological process in which bacteria is used to treat the water. A top layer of microbes called Schumtzdecke (or bio-film) is allowed to be formed. Water is passed through this layer, and bacteria, protozoa and viruses are removed which essentially produces clean water (though it is still advised to go through the disinfection process. The disadvantages of slow sand filtration is that it requires a large land area and cleaning of the bio-film every few of months because it gets too thick and the flow rate decreases. Also, the water flow rate for slow sand filtration is between 0.1 and 0.3 cubic metre per hour which is too slow to keep up with modern society's rapidly increasing demands for clean water. For these reasons, rapid sand filtration is used in modern-day treatment plants. Rapid sand filters are built box-like concrete structures whereby overflow from the sedimentation tank is passed through varying porous layers and the final filtered water is sent to disinfection (Britannica, 2020). The advantages of rapid filtration are: relatively small land area is required and can take flowrates up to 20 000 litres per hour according to SDWF (2017a). Even though rapid filtration removes almost all contaminants effectively, it still requires disinfection to remove bacteria and viruses. Figure 1 below shows a typical schematic of a rapid sand filtration structure.

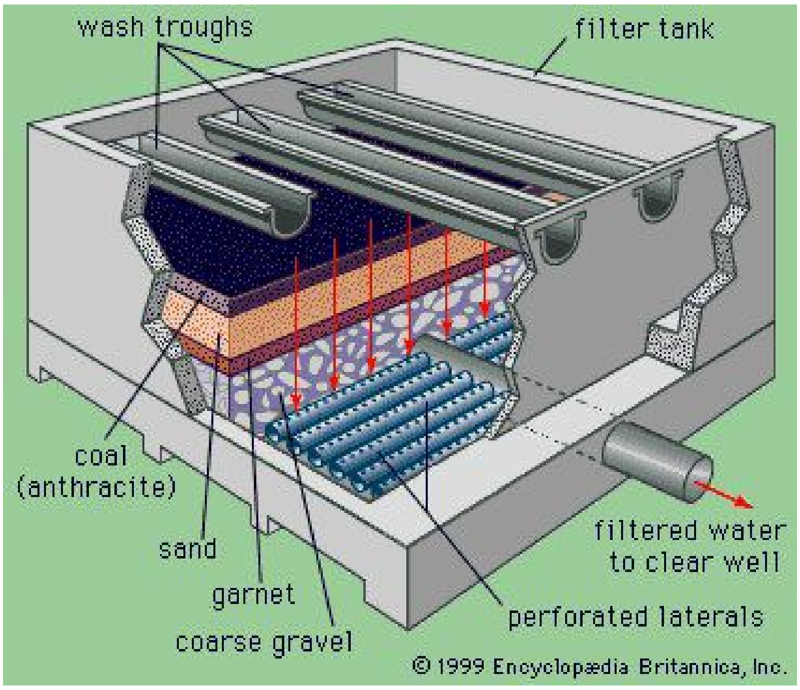

Figure 1: An illustration of a typical rapid sand filtration structure (adapted from Britannica, 2020).

The final step in the water treatment process is disinfection. It is accomplished by either using chlorine or chlorine compounds, ozone, or ultraviolet radiation to filtered water (Britannica, 2020). Chlorine is the most commonly used disinfection method because of numerous reasons: it is highly effective in killing bacteria or viruses, relatively inexpensive to use, easily used on a plant and is quick-fix solution during water emergencies such as mixing of treated and raw water (SDWF, 2017b). Ozone gas can be used as disinfection, however, it is an unstable molecule and can not be easily stored (Britannica, 2020). For this reason ozone is more expensive than chlorine. The benefits of using ozone is that it reduces the taste and odor of the water and leaves no residual, unlike chlorine. Ultraviolet radiation, like ozone, kills bacteria and viruses while leaving no residual in the water. But its high cost and maintenance has made it unfavorable compared to chlorine or ozone.

2.2 Coagulation

Coagulation is a process that involves the adding of chemicals called coagulants to remove the turbidity of water. These chemicals have a net positive charge and neutralise the net negative charge of the colloidal particles in the water. During this reaction (often referred as flocculation) the particles come together and form a larger, heavier particle (or floc) that can settle to the bottom while the clearer water is moved onto the filtration process (SDWF, 2017a). The settling process (sedimentation) usually occurs in the settling tank. Figure 2 bellow illustrates the process of coagulation, flocculation and sedimentation using Moringa as a coagulant.

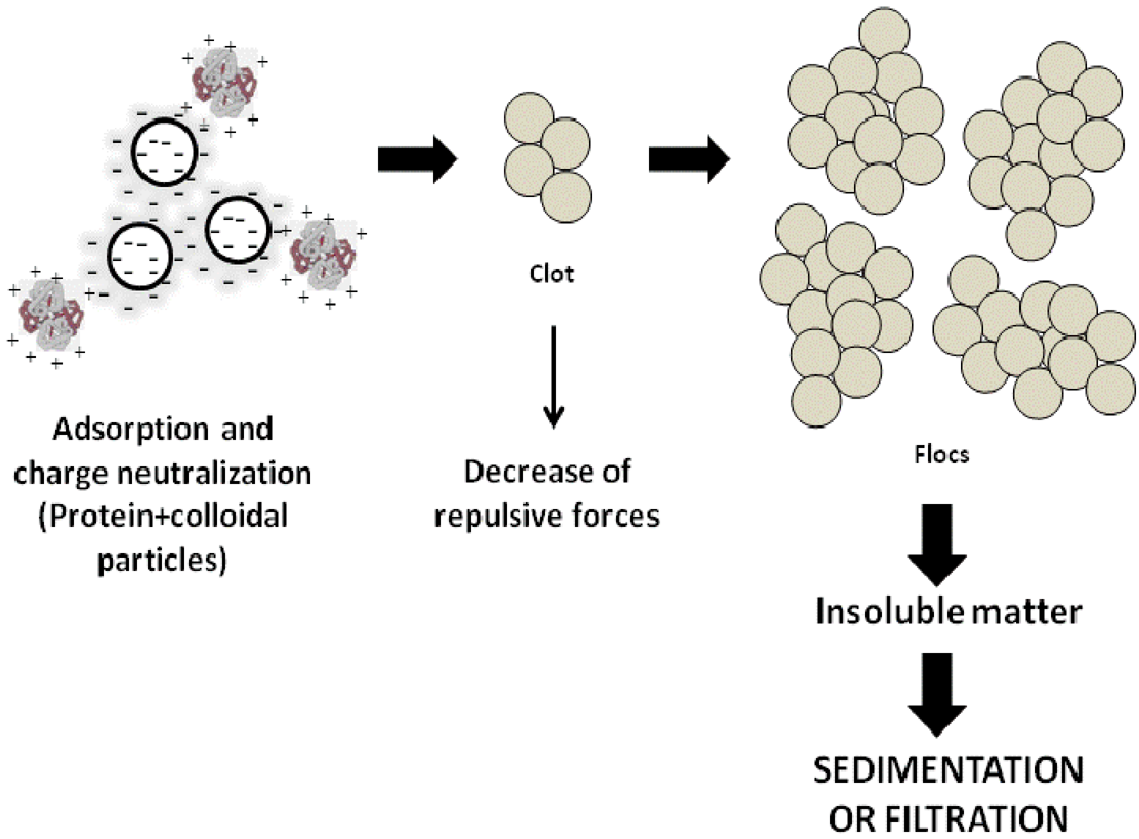

Figure 2: Coagulation, flocculation and sedimentation mechanism of Moringa Oleifera (adapted from Santos *et al*, 2013).

According to Britannica (2020), coagulation is accomplished in two stages: rapid mixing and slow mixing. Rapid mixing is done to rapidly mix the coagulants with water and ensure chemical reaction occurs. On the treatment plant this process is done by adding the coagulant to the pump and the propellers do the mixing or a small flash-mix tank is used. After rapid mixing, a longer period of gentle agitation is required to promote the process of flocculation and enhance the growth of the floc. This slow mixing occurs in a flocculation tank that consists of a shaft-driven paddles that slowly agitates the water. After this step, the water flows to the sedimentation tank.

2.3 Moringa Oleifera

The Moringa Oleifera tree is originally native to the Northern parts of India. However, it now grows in most sub-tropical countries, especially in developing countries. There are over 14 species variations of the Moringa tree and it been found that they have varying coagulating properties that are attributed on the geographical location, climate, altitude, and soil characteristics (Bratby, 2016). The Moringa tree provides a whole multitude of uses such as fodder for domestic animals, traditional herbal remedies, cooking oil, and many more. One such important use is the harvesting of the Moringa seeds to be used as a natural coagulant.

The seedpods of the Moringa tree are often allowed to dry naturally before it is harvested. There afterwards, the seeds are easily removed from the pods and is either shelled, crushed or grounded up into a powder. Water is then mixed with the powder to create water soluble proteins that has an overall net positive charge (Bratby, 2016).

An interesting study was conducted by Narasiah, Voegal & Kramadhati (2003) compared the coagulation properties of Moringa seed extracts from Burundi and Madagascar. Laboratory were conducted on the coagulation of kaolin turbid water using the two different seed extracts, as well as testing with shelled and non-shelled seeds . The results found that the shelled seeds were more effective in reducing the turbidity of water and that the Burundi seeds are far superior than the Madagascar seed for turbidity removal. Therefore it can be concluded that the type of Moringa seed used does play a role in the turbidity removal of water.

According to Bratby (2016), Moringa coagulants have been reported to be ineffective in treating water with low turbidity. This may be due to the low molecular weight of the coagulant and its weak charge neutralisation that forms smaller and lighter flocs (which in turn does not settle).

2.4 Ferric Chloride, $FeCl_3$

Metal coagulants commonly fall under two categories: those that based on iron and those based on aluminium. The coagulant $FeCl_3$ is commercially available in solid (crystal), anhydrous or liquid form (Bratby, 2016). This coagulant is highly corrosive and should be handled and stored with extreme care. The commercial liquid grade ferric chloride is supplied typically as 40 to 43 % by mass $FeCl_3$.

The formation of opposite charges of Ferric Chloride is shown below (Peavy, Rowe & Tchobanoglous, 1985):

$$\mathrm{FeCl_3} \longleftrightarrow \mathrm{Fe^{3+}} + 3\,\mathrm{Cl^-} \tag{1}$$

$$\mathrm{Fe_3}^+ + \mathrm{H_2O} \longleftrightarrow \mathrm{Fe(OH)_2}^+ + \mathrm{H^+} \tag{2}$$

$$\mathrm{Fe_3}^+ + 2\,\mathrm{H_2O} \longleftrightarrow \mathrm{Fe(OH)_2}^+ + 2\,\mathrm{H^+} \tag{3}$$

$$7\,\mathrm{Fe_3}^+ + 17\,\mathrm{H_2O} \longleftrightarrow \mathrm{Fe_7(OH)_{17}}^{4+} + 17\,\mathrm{H^+} \tag{4}$$

The first reaction is when the ferric chloride coagulant is added to water. Ionization of $FeCl_3$ in the water reacts to form iron-cations (Fe^{3+}) and chloride anions (Cl^-). The (Cl^-) will form or combine with other cations and the (Fe^{3+}) cations will form a wide variety of aquometallic ions and hydrogen. These aquometallic ions have a great affinity for negative surfaces and will bind with them to neutralize the surface charge. In the context of flocculation, these aquometallic ions will bind with colloidal solids and form large flocs that will settle (Peavy *et al*, 1985).

2.5 Sedimentation

Sedimentation is a process whereby suspended particles in water are allowed to settle (out of suspension) under the effect of gravity (IWA, 2020). When the particles settle out of suspension it forms sediment. In water treatment, this sediment or sludge can be assisted by mechanical means and is referred to as thickening.

In water treatment, sedimentation can be used to reduce the concentration of colloidal suspension before coagulation. This is beneficial because less coagulant is required and therefore coagulant cost are reduced. There are a variety of sedimentation techniques that are implemented and include: horizontal flow, radial flow, inclined plate, ballasted floc and floc blanket sedimentation. However, no further investigation on these different techniques will be done as they are beyond the scope of this experiment.

There are four types of sedimentation; namely type 1, type 2, type 3 and type 4 settling. For the scope of this experiment only Type 1 and 2 settling will be considered. Type 1 settling or discrete settling occurs for all solid particles suspended in water. If the particles are big and heavy enough they will settle freely under the influence of gravity. However, even the largest of solid suspended particles (or colloidal suspension) have an average particle size of 0.0001 mm and therefore have a very slow settling residence time (i.e. very slow settling velocity)- which is not viable in industry (Peavy *et al*, 1985). Kaolin mineral clay has an average particle size of 0.00001 mm (Bratby, 2016) and will need the aid of a coagulant to settle. Type 2 settling or flocculant settling is when a coagulant is used to aid settling by forming a larger, heavier particle called a floc.

2.6 Turbidity Test

Turbidity is a measurement of the cloudiness of water and is a good indicator of the quality of the drinking water. According to Myre & Shaw (2006), the equipment used to measure turbidity is expensive and often provides unnecessary measurements that are more accurate and precise. The unit of measurement for turbidity is reported in nephelometric turbidity units (NTU). On average, a human (with the naked eye) can begin to see turbidity levels at 5 NTU and above. At 2000 NTU, water is considered completely opaque. There are different methods that can be used to measure the turbidity of water and are summarised in Table 1.

2.6.1 Length-to-Turbidity Conversion

In order to convert the measured heights (in cm) to NTU, using the methods mentioned in Table 1, *Length-to-Turbidity Conversion Charts* can be used. The NTU values for the measured depths can be determined by using Table 2. Myre & Shaw (2006) proposed Equation 5 to convert the measured depths (in cm) to NTU. However, Equation 5 is only applicable for depths between 6.25 cm and 60 cm. Depths lower than 6.25 cm or above 60 cm can not be accurately determined using Equation 5.

$$\text{Depth/Height in Centimeters} = 244.13(NTU)^{-0.662} \tag{5}$$

Table 1: The different methods to measure turbidity of water.

Method and Description	Advantage	Disadvantage
Jackson Candle Turbidimeter A graduated cylinder is placed over a burning candle. Turbid water is poured into the cylinder and the reading (height of the water) is taken once the burning candle is no longer visible.	Historical method.	No longer a conventional method. Can't measure less than 25 NTU.
Nephelometer A light beam is passed through the turbid water and the amount of scattered light at a 90° angle is measured.	Very accurate. Some devices are portable. Can measure very low turbidity.	Expensive device and easily damaged. Requires a power source to operate. Constantly needs to be calibrated.
Secchi Disk A circular black and white disk. It is lowered into the water sample and the maximum distance in which the disk is no longer visible is recorded.	Easy to operate. Portable and cheap. No consumables.	Less accurate. Can not be used in shallow waters or if there are currents. Can not be used for small sample sizes.
Turbidity Tube It is a combination of the Secchi disk and Jackson Candle methods. The Secchi disk is attached to the bottom of the tube and the turbid water is poured in. The height in which the disk is no longer visible is recorded.	Easy to operate. Portable and cheap. No consumables. Suitable for different kinds of water sources	Less accurate, can only measure NTU of 5 and above (what is visible to the naked eye).

Table 2: Length-to-Turbidity Conversion Chart (adapted from Utah State University Extension, 2016.)

Centimeters	NTU
< 6.25	> 240
6.25 to 7	240
7 to 8	185
8 to 9.5	150
9.5 to 10.5	120
10.5 to 12	100
12 to 13.75	90
13.75 to 16.25	65
16.25 to 18.75	50
18.75 to 21.25	40
21.25 to 23.75	35
23.75 to 26.25	30
26.25 to 28.75	27
28.75 to 31.25	24
31.25 to 33.75	21
33.75 to 36.25	19
36.25 to 38.75	17
38.75 to 41.25	15
41.25 to 43.75	14
43.75 to 46.25	13
46.25 to 48.75	12
48.75 to 51.25	11
51.25 to 53.75	10
53.75 to 57.5	9
57.5 to 60	8
Over 60	6

2.7 The Optimal Dosage and Optimal Hindered Settling Velocity

According to Peavy *et al* (1985), adding more coagulant does not necessarily equate to better or faster flocculation of the floc particles. At high colloidal concentrations, charge neutralization between the coagulant and colloidal particle occurs initially, but continually adding more coagulant may result in charge reversal. As a result, reversal of the flocculation process and can even increase the turbidity of the water. Therefore, the largest dosage of coagulant added does not imply the optimal dosage. Peavy *et al* (1985) suggest that the optimal coagulant dosage is the dosage that produces he lowest turbidity in the water and therefore this method was used to determine the optimal coagulant dosage for the experiment.

The optimal hindered settling velocity (u_H) is determined using the optimal coagulant dosage. To determine the optimal hindered settling velocity, the most convenient method is to use the batch-settling test. The batch-settling test is when batch of solids in suspension are allowed to settle, most cases using a measuring cylinder Rhodes (1999). The change in interface height between turbid and clear liquid layers should be recorded (Torfs & Daigger, 2016). Thereafter, the interface heights (h_i) is plotted against time (t). Once the graph has been plotted, tangent lines will be drawn for at least 10 height intervals. The gradient of the tangent line is determined by $\Delta h/\Delta t$, with $h_0 = 0$ m and $t = 0$ s used as the initial reference points. The gradient represents the hindered settling velocity (u_H) of the flocs formed during sedimentation. Once the optimal coagulant dosage and the hindered settling velocity are determined, the sedimentation tank can be designed.

2.7.1 Further Analysis of the Height-Time Curve

The simple batch settling test can provide all the information required to design a sedimentation tank (thickener) for the separation of particles from a fluid. However, it is critical to determine the concentration of the particulate matter (at each specific interface height) that is associated with each tangent velocity (u_H) (Rhodes, 1999). Referring to Figure 3, at time t the interface between clear liquid and suspension of concentration C is at a height h from the base of the vessel. As previously mentioned above, the velocity of the interface is the slope of the tangent curve:

$$\text{velocity of interface} = \frac{dh}{dt} = \frac{h_1 - h}{t} \tag{6}$$

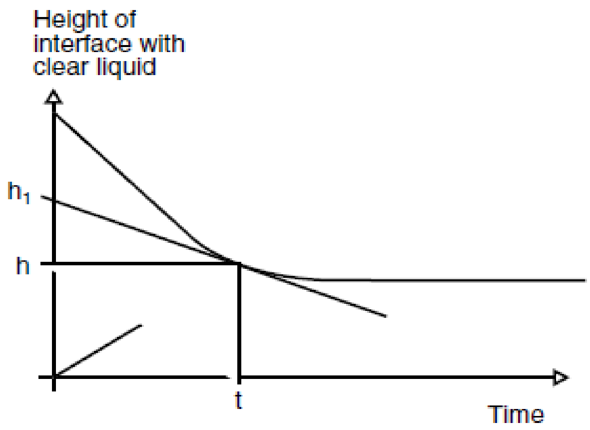

Figure 3: Analysis of batch settling test: Height-Time curve (adapted from Rhodes, 1999).

Equation 6 is equal to the velocity of the particles at the interface relative to the vessel wall (U_p):

$$U_p = \frac{h_1 - h}{t} \tag{7}$$

Now consider a plane of higher concentration that rises from the bottom of the vessel. The plane of concentration C rises a distance h at time t. Thus, the velocity of the particles relative to the plane as it passes through the suspension is:

$$\text{velocity of particles relative to plane} = U_p + \frac{h}{t} \tag{8}$$

Referring to Figure 4, the volume of particles (having a concentration C) that pass through the plane is:

$$\text{volume of particles through the plane} = A\left(U_p + \frac{h}{t}\right)Ct \tag{9}$$

The total volume of particles in the test is equal to C_0h_0A, therefore substituting this into Equation 9:

$$C_0h_0A = A\left(U_p + \frac{h}{t}\right)Ct \tag{10}$$

Substituting Equation 7 into Equation 10 and re-arranging gives concentration of the particulate matter C_i at a specific interface height h_i :

$$C_i = \frac{C_0 h_0}{h_i} \tag{11}$$

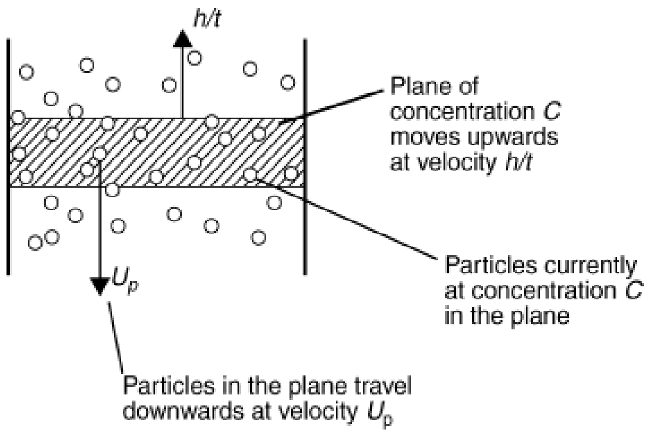

Figure 4: Analysis of batch settling test: the relative velocity of a plane concentration at a specific height (adapted from Rhodes, 1999).

2.8 Design of Sedimentation Tank

The settling of colloidal suspension into a clear liquid and a concentrated stream of solids (slurry) is called sedimentation. If the desired product is a clear liquid the term clarification is used and if the product is a concentrated slurry stream the term thickening is used (Rhodes, 1999). When designing a sedimentation tank, the key parameter is the cross-sectional surface area (A) and the depth of the tank is not of concern. However, according to (Christian, 1994) the depth of the tank is usually 2.5 to 5 m. This allows enough space to store the solids at the bottom of the unit.

Referring to Figure 5 a solids mass balance over the thickener gives :

$$Q_f c_f = Q_u c_u + Q_o c_o \tag{12}$$

Normally the aim of a thickener is to have no solids in the overflow, i.e. $c_o = 0$.

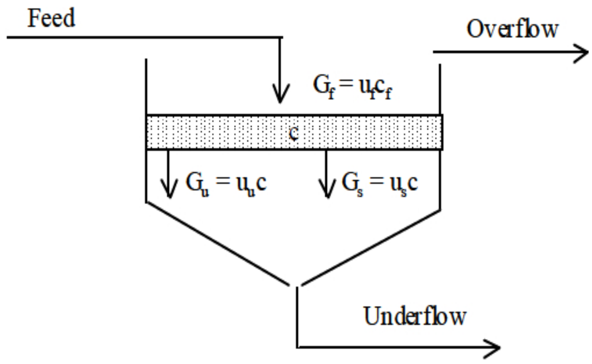

Figure 5: Schematic of a typical continuous thickener (adapted from Rhodes, 1999).

According to Christian (1994), once the hindered settling velocity and concentration is determined for different interface heights, a mass flux versus concentration curve must be plotted. Reason for this is to determine the cross-sectional area of the thickener. Mass flux G_s of the settling floc is determined using Equation 13.

$$G_s = C_i u_s \tag{13}$$

According to Rhodes (1999), to get the minimum cross-sectional area of a thickener, the maximum feed flux must be determined (operated at critical load). The maximum flux is determined when the line joining the underflow concentration (on the x-axis) touches the feed flux curve as shown in Figure 6.

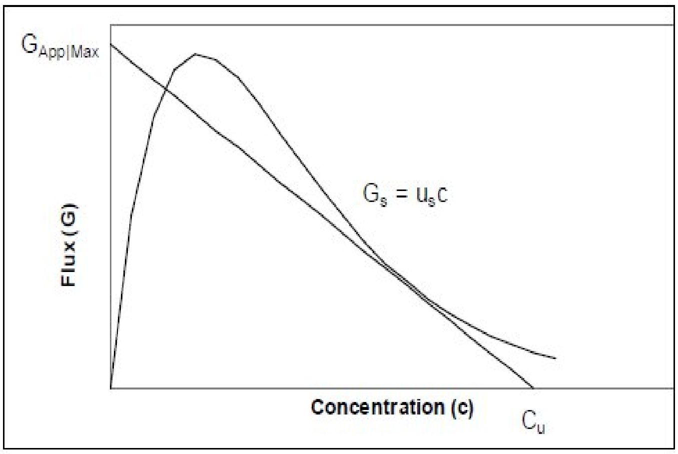

Figure 6: Settling flux versus concentration curve: graphical method to determine minimum area required for a thickener (adapted from Rhodes, 1999).

Knowing the maximum flux $G_{max,s}$, the minimum cross-sectional area of a thickener is calculated as:

$$A_{min} = \frac{Q_f c_f}{G_{max,s}} \tag{14}$$

The minimum cross-sectional area calculated in Equation 14 is multiplied by a safety factor range of between 1.2 - 1.5 (Rhodes, 1999). This ensures that the thicker operates safely and far away from overloading conditions.

3 Experimental Plan

3.1 Apparatus and Material

The material required to perform the experiment is described below:

- Kaolin G3 clay (500 g) was used as colloidal suspension in water, i.e. simulate typical turbid water to be treated during the water treatment process.
- Moringa seed powder (100 g) was used as the natural plant-based coagulant to treat turbid water.
- $FeCl_3$ powder (20 g) was used as the chemical (commercial) coagulant to treat turbid water. It was used as the baseline experiment to which all other experiments using Moringa or Moringa-$FeCl_3$ 50:50 combination coagulants was compared too.
- Water (1000 ml) was used for all batch settling tests.

The following equipment were used to perform the experiment:

- Measuring ruler (30 cm).
- Tracing paper, sellotape and a marker were used to mark the different height on the cylindrical beaker.
- A Cylindrical beaker (85 mm ID, 215 mm height) was used as the batch-settling jar.
- A small jewellery scale (max 500 g $\times$ 0.1 g resolution) to weigh the material.

- Shot glass $\times 3$ for holding the material that was weighed.
- Spoon$\times 3$.
- Mixing rod.
- Measuring jug (2000 ml).
- A phone camera to record all the batch settling tests and be able to determine the hindered settling velocity of the optimal coagulant dosages.

3.2 Planning

The independent variables (also referred to as the control variables) of this experiment were the coagulants used to treat the turbid water. Specifically the different dosages of coagulants ($FeCl_3$, Moringa and $FeCl_3$-Moringa 50:50 combination) used to treat the turbid water. $FeCl_3$ as a coagulant was selected as the baseline experiment to which all other experiments using different coagulants would be compared to. The reason for this is because $FeCl_3$ is a commercially used coagulant that is known to be effective in treating turbid water. Out of intuition, the dosage ranges to be tested for $FeCl_3$ ranged from 1 g to 5 g (6 g was left over as back-up in case one of the experiments failed). Reason for this was because of the limited amount of $FeCl_3$ provided, i.e. 20 g. Similarly, the dosage ranges for $FeCl_3$-Moringa 50:50 combination was selected to be 1 g to 6 g. The Moringa dosage ranges to be tested were 2.5 g to 10 g. The reason for this selection was due to the fact that there was more Moringa powder provided than $FeCl_3$. Moreover; out of intuition, Moringa is less effective than $FeCl_3$ as a coagulant because it is not used commercially and therefore requires higher dosages.

The dependent variables (also known as the manipulated variables) of this experiment were the turbidity's measured after each batch-settling test and the hindered settling velocity of the optimal dosage of each different coagulant run. These two variables are dependent on the amount of coagulant (the independent variable) added to the turbid water. It was decided to use the Secchi disk method to measure the turbidity of the water after each batch-settling test because of its convenience and relative accuracy.

The experimental variables that remained constant, sometimes referred as parameters, throughout the experiment were the volume of the water and the concentration of the Kaolin clay in the water. Moreover, the temperature of the turbid water was assumed to be constant with a temperature range of about 25-27 °c.

3.3 Methods

Due to the limitation of amount coagulant given per student, specifically the 20 g $FeCl_3$, it was decided to split the experimental work between the members of Group E doing Experiment 2. T. Singh from group 4 performed the different dosages $FeCl_3$ coagulant, N. Campher from group 21 performed the Moringa runs and X. da Silva from group 23 performed 50:50 ratio combination of $FeCl_3$ and Moringa. In order to compare the results amongst the three groups accurately, it was decided to standardize the experimental apparatus, conditions and procedure. The water used was 1000 ml and it was determined to add 2.5 g Kaolin clay to ensure a 2.5 g l^{-1} colloidal suspension concentration. The batch-settling jar had to have a internal diameter of between 75 to 85 mm and a height sufficient enough to allow for 1000 ml of water to be added. This range was selected out of convenience due to what was easily available to all three members at home. The subsequent procedure that was followed to perform all the different coagulant dosage experiments is described below:

1. The cylindrical beaker will be rinsed to eliminate dust contaminants before each batch test.
2. Next, using the measuring jug, the 1000 ml water is poured into the beaker.
3. Set the scale to 0 with the empty shot glass. Then weigh 2.5 g kaolin into the empty glass and thereafter into the water.
4. Rapidly stir and mix the kaolin in the water for 30 seconds to ensure even distribution.
5. Using the traced paper with its associated markings (indicating the different heights), attach it onto the beaker with the sellotape. Note, this step only needs to be completed once.
6. Using the scale, weigh the appropriate amount of coagulant dosage to be added using the empty shot glass.
7. Add the coagulant into the turbid water and stir rapidly for 2 minutes to allow the coagulant to be thoroughly mixed (this is to simulate rapid mixing).
8. Next, start the timer and record the initial interface height, $h_0 = 0$, at time zero ($t = 0$). The kaolin water interface will be taken at the following time intervals: 0, 0.5, 1, 2, 3, 4, 5, 10, 15, 20, 30 and 45 min (Torfs & Daigger, 2016).
9. Steps 1 to 9 were repeated for different experiments using varying dosages of *Moringa*, $FeCl_3$ and $FeCl_3$-Moringa combination as coagulants.

10. After the experiments are completed and all the readings have been recorded, the experimental results were graphed by plotting the interface height against time for each dosage used (Torfs & Daigger, 2016).

4 Results and Discussion

4.1 $FeCl_3$ Coagulant

Table 3: Measured turbidity values (in NTU), using the Secchi disk, for all the different $FeCl_3$ dosage runs.

Dosage (g)	Depth (cm)[a]	Turbidity (NTU)
1	4.0	>240[c]
2	4.5	>240[c]
3	6.8	223[b]
4	6.0	>240[c]
5	3.9	>240[c]

[a] Measured using Secchi disk [b] Calculated using Equation 5
[c] Extrapolated using Table 2

Table 3 shows the measured turbidity results for all the $FeCl_3$ dosage runs. The optimal dosage of coagulant was found to be 3 g $FeCl_3$ because it produced the lowest measured turbidity out of all the other dosages. At first glance it can be deduced that there seems to be a somewhat linear relationship between the amount of dosage added and the measured turbidity. As the dosage increases, the measured depth increases and therefore the turbidity decreases (which is desired). This is confirmed visually using Figure 7 and the *scipy.stats.linregress* module (python) was used to test the extent of linearity. A standard linear regression of 0.47 was found, a standard linear regression of 1 indicates perfect linearity. However, it is not possible to fully conclude that there is a linear relationship because too few tests were conducted at different dosages. It can be seen that at 5 g dosage the depth decreases, i.e. increased turbidity. This could indicate to much coagulant and a reversal in flocculation, but higher dosages need to be tested to support this claim. Moreover, repeatability of the results was not done due to the limited amount of $FeCl_3$ provided and therefore the results are not accurate.

Figure 8 was plotted in order to determine the optimal hindered velocity. It was decided to use ten different heights to determine ten different velocities (tangent lines). However, more heights could of been done to have more data points and a more accurate curve. Further analysis is discussed later in the report.

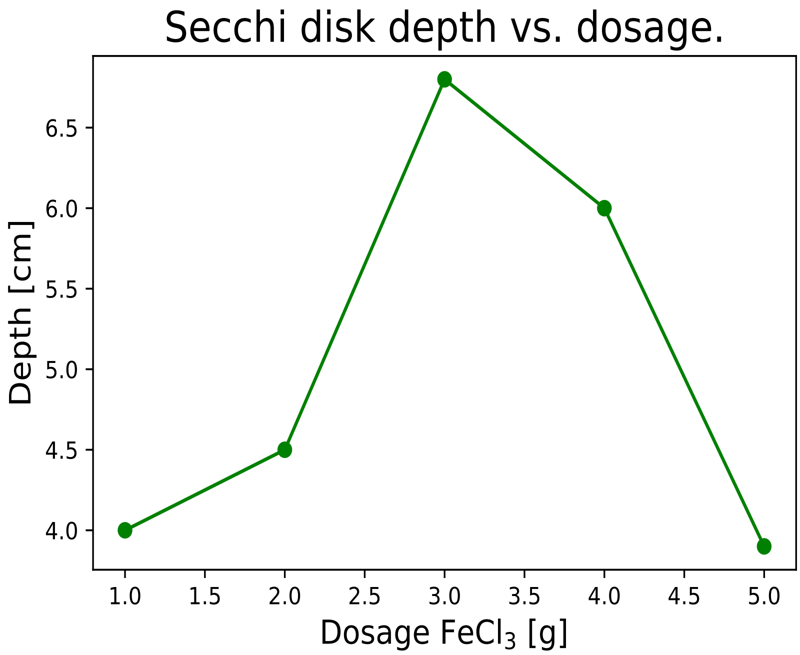

Figure 7: Relationship between dosage and turbidity (in terms of depth) for $FeCl_3$.

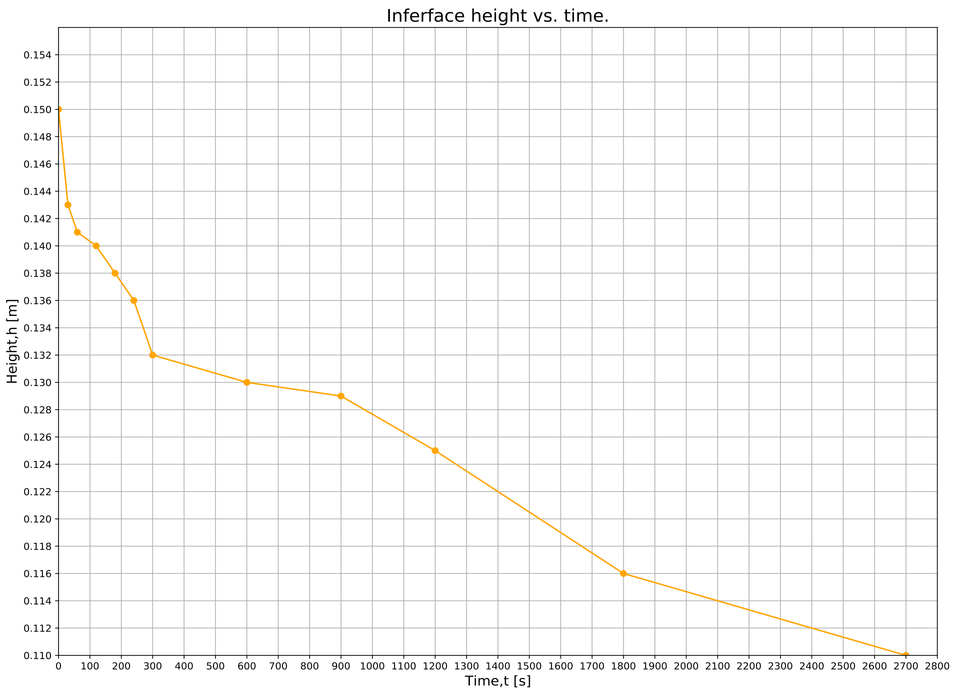

Figure 8: Detailed interface height versus time curve used to determine the hindered settling velocity of 3 g $FeCl_3$.

4.2 Moringa coagulant

From Table 4, it was found that optimal coagulant dosage is between 5 g and 6 g Moringa. However, 5 g was decided to be the optimal dosage because less Moringa was required as a coagulant to achieve the same desired turbidity as 6 g Moringa. Repeatability of the results were not done, even though enough Moringa powder was provided to allow it. Reason for this was to keep the experimental procedure the same for the other coagulant dosage runs. From Figure 9 it can be seen that there seems to be a non-linear relationship between the amount of dosage added and the measured turbidity. This is confirmed by a standard linear regression of 0.34. Interesting to note from Figure 9, the turbidity decreases linearly after 6 g Moringa. This could indicate that there is a linear relationship between the amount of dosage added and the measured turbidity, but to confirm this more results should be done at lower dosages (before 5 g and 6 g dosages, which represents the threshold in coagulant added) and at higher dosages. Figure 10 was plotted in order to determine the optimal hindered velocity.

Table 4: Measured turbidity values (in NTU), using the Secchi disk, for all the different Moringa dosage runs.

Dosage (g)	Depth (cm)[a]	Turbidity (NTU)
2.5	8.0	175[b]
5	11.0	108[b]
6	11.0	108[b]
7	9.5	135[b]
7.5	9.0	146[b]
10	6.0	>240[c]

[a] Measured Secchi disk [b] Calculated using Equation 5
[c] Extrapolated using Table 2

Higher concentrations of Moringa as a coagulant was required as compared to $FeCl_3$. This could be the reason why $FeCl_3$ is used commercially and not Moringa. However, the 5 g Moringa did achieve a lower turbidity than the 3 g $FeCl_3$.

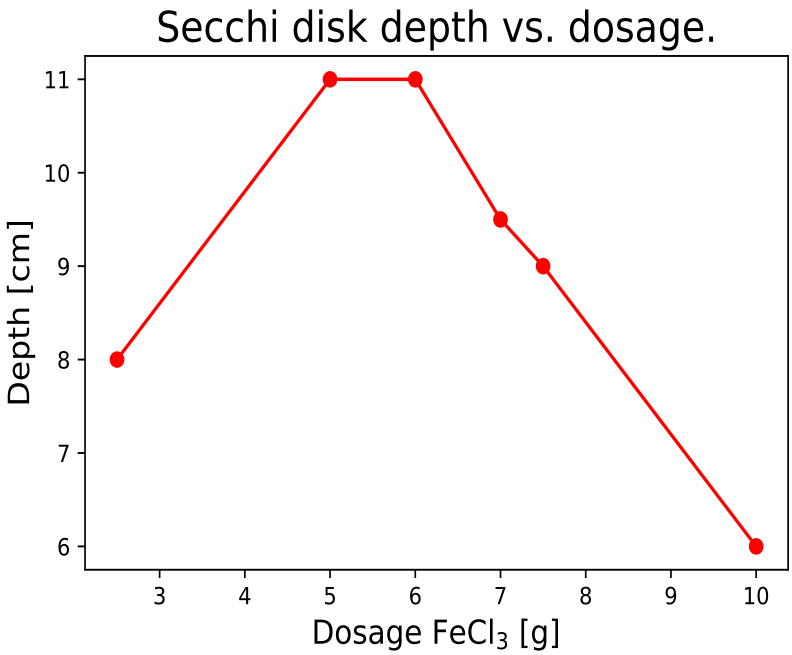

Figure 9: Relationship between dosage and turbidity (in terms of depth) for Moringa.

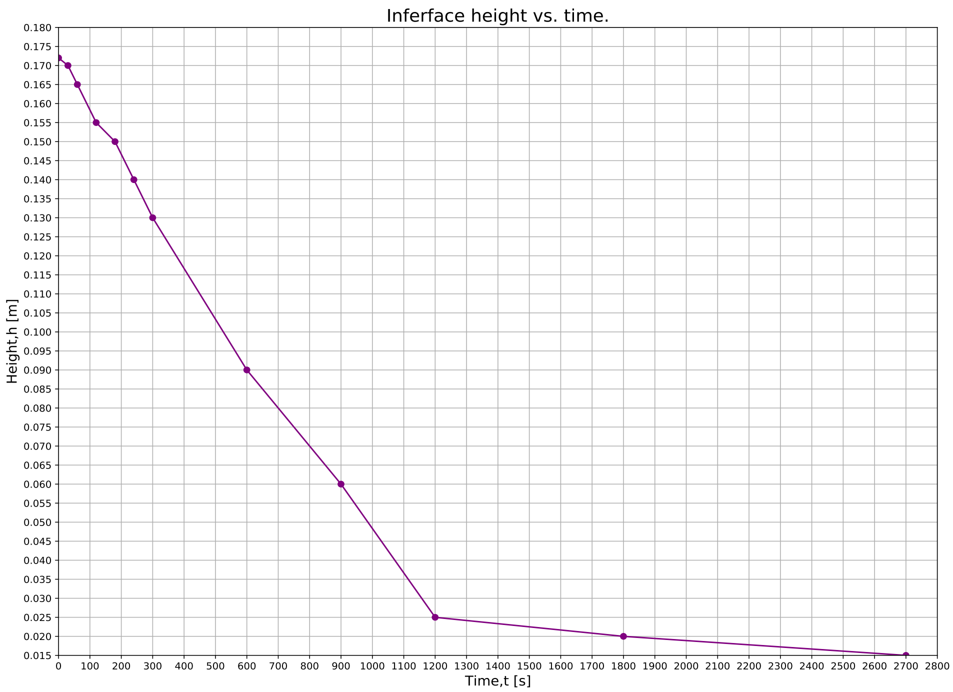

Figure 10: Detailed interface height versus time curve used to determine the hindered settling velocity of 5 g Moringa.

4.3 $FeCl_3$-Moringa Combination Coagulant

Referring to Figure 5 it can be seen there is a linear relationship between the amount of coagulant added and turbidity. The more dosage added, an increase in turbidity was observed. Unfortunately for all the $FeCl_3$-Moringa batch-settling tests a clear interface layer could not be seen. However, coagulation did take place because a clear sediment layer did form at the bottom after 45 minutes (as shown in Figure 11). Therefore the hindered settling velocities could not be determined.

Table 5: Measured turbidity values (in NTU), using the Secchi disk, for all the different $FeCl_3$-Moringa combination dosage runs.

Dosage (g)	Depth (cm)[a]	Turbidity[b] (NTU)
1	2.8	>240
2	2.6	>240
3	2.6	>240
4	2.2	>240
5	2.2	>240
6	1.0	>240

[a] Measured Secchi disk
[b] Extrapolated using Table 2

Figure 11: 0.5 g $FeCl_3$ and 0.5 g Moringa combination in turbid water.

5 Design of Sedimentation Tank

A few assumptions were made in the sedimentation tank design for both the $FeCl_3$ and Moringa coagulants. In order to determine the minimum cross sectional area of the tanks and be able to use the graphical method (mentioned in the theory), it was assumed no solid products (slurry) was left in the overflow stream. However, in practice this is not the case and solids will be present in the overflow stream, hence the need for filtration in the water treatment process. Secondly, the feed concentration was assumed to be a combination (100 % flocculation occurs) of the 2.5 g Kaolin clay (added during the batch test) and the mass of each optimal coagulant. This total mass was then divided by a total volume of 1000 ml (volume chosen during the batch test) to simulate the floc concentration (solid concentration) in the feed stream to the sedimentation tank. This deviates slightly from the original design specifications, but this assumption provides a more accurate representation of the solid suspension entering the thickener as not all the colloidal suspension are floc particles now. However, Since the desired product is a concentrated slurry stream, the sedimentation tank will be referred to as a thickener throughout this section.

5.1 Sedimentation Tank Design using $FeCl_3$

The hindered settling velocity for 3 g $FeCl_3$ coagulant was determined and is shown in Table 6. The feed concentration (c_f) was determined to be 5.5 $\mathrm{kg\,m^{-3}}$. The feed concentration also represents initial concentration for the initial interface height (C_0), this was used to calculate the concentration of solids at different interface heights (C_i).

The calculated mass flux and concentrations from Table 6 were used to plot Figure 12. Since no underflow concentration (c_u) was specified in the design specification (refer to problem statement), a underflow concentration of 7.10 $\mathrm{kg\,m^{-3}}$ was selected. Reason for this choice was to choose a realistic value that was interpolated within the determined experimental data. The minimum cross-sectional area of the thickener using 3 g $feCl_3$ was calculated to be 27677 m^2. This was calculated using Figure 12 and Equation 14. Multiplying by a safety factor of 1.4, the actual cross sectional area of the thickener is 38748 m^2.

Table 6: Hindered settling velocity, concentration and settling flux for the 3 g $FeCl_3$ batch test.

Height[a] (m)	Hindered settling velocity[b] $\times 10^{-6}$ ($m\,s^{-1}$)	Concentration[c] ($kg\,m^{-3}$)	Settling mass flux[d] $\times 10^{-5}$ ($kg\,s^{-1}\,m^{-2}$)
0.150	400.0	5.50	220.0
0.146	90.00	5.65	50.85
0.142	32.65	5.81	18.97
0.138	19.72	5.98	11.79
0.134	10.00	6.15	6.150
0.130	7.692	6.35	4.884
0.126	5.926	6.55	3.882
0.122	4.444	6.76	3.004
0.120	3.571	6.88	2.457
0.116	2.143	7.11	1.524

[a] Selected reference height from Figure 8
[b] Tangent gradient from Figure 8
[c] Calculated using Equation 11
[d] Calculated using Equation 13

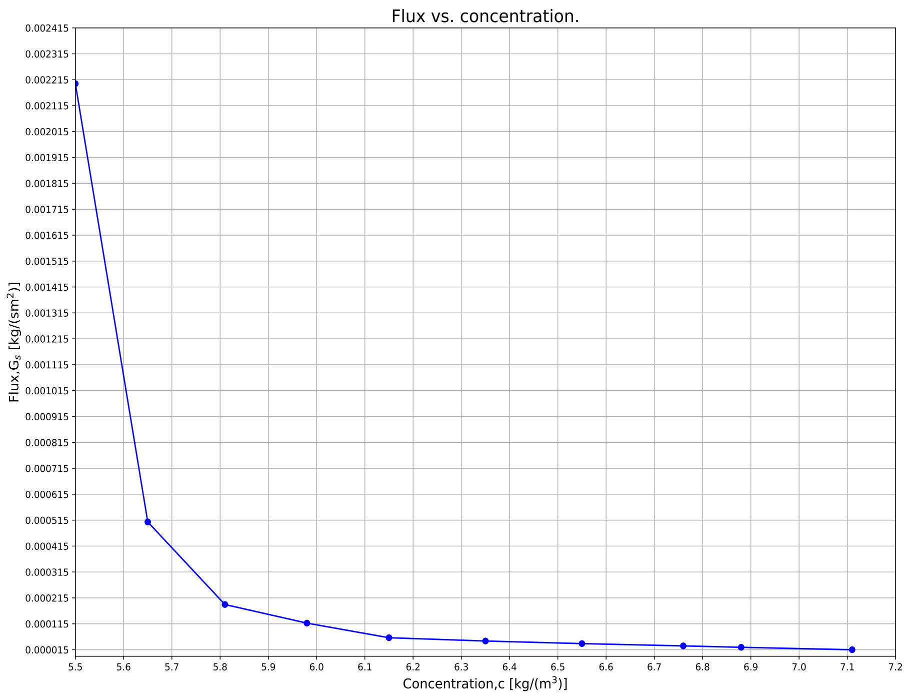

Figure 12: Mass flux versus concentration curve for 3 g $FeCl_3$.

5.2 Sedimentation Tank Design using Moringa

The same procedure mentioned above was used to calculate the minimum cross-sectional area for 5 g Moringa dosage. The feed concentration (c_f) was determined to be 7.5 $\mathrm{kg\,m^{-3}}$ and the underflow concentration was chosen as 15.50 $\mathrm{kg\,m^{-3}}$. Calculations of hindered settling velocities at different interface heights is illustrated in Table 7 and the mass flux-concentration curve is plotted in Figure 13. The minimum cross-sectional was calculated to be 4879 $\mathrm{m^2}$, multiplied by a safety factor of 1.4 the actual cross-sectional area is 6831 $\mathrm{m^2}$.

Table 7: Hindered settling velocity, concentration and settling flux for the 5 g Moringa batch test.

Height[a] (m)	Hindered settling velocity[b] $\times 10^{-5}$ ($\mathrm{m\,s^{-1}}$)	Concentration[c] ($\mathrm{kg\,m^{-3}}$)	Settling mass flux[d] $\times 10^{-4}$ ($\mathrm{kg\,s^{-1}\,m^{-2}}$)
0.170	13.48	7.50	10.11
0.160	11.60	7.97	9.245
0.150	10.38	8.50	8.823
0.140	9.615	9.11	8.759
0.130	8.712	9.81	8.547
0.120	7.836	10.63	8.330
0.110	6.985	11.59	8.096
0.100	6.159	12.75	7.853
0.090	5.357	14.17	7.591
0.080	4.577	15.94	7.296

[a] Selected reference height from Figure 10
[b] Tangent gradient from Figure 10
[c] Calculated using Equation 11
[d] Calculated using Equation 13

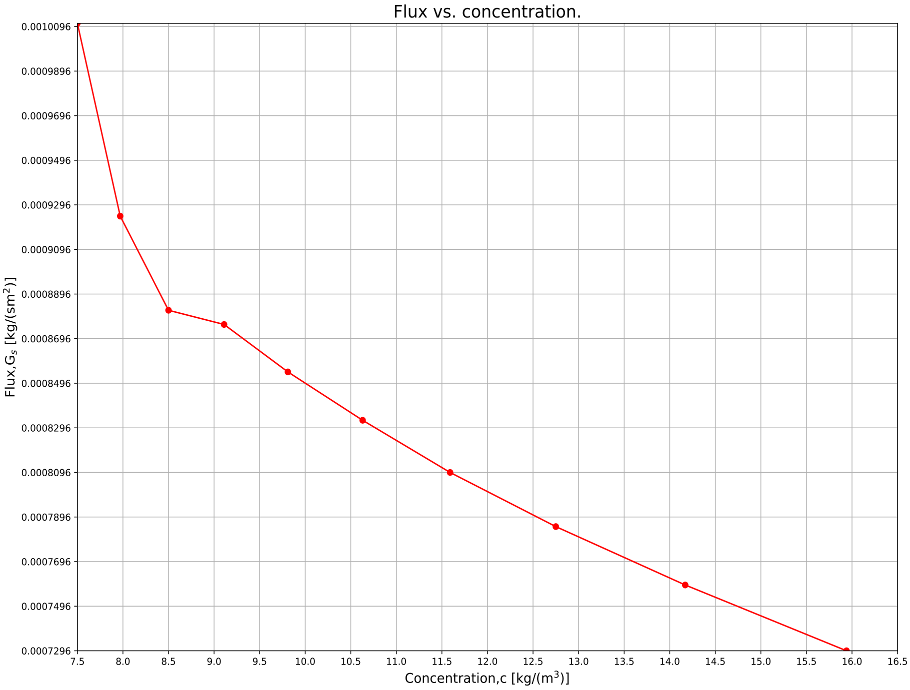

Figure 13: Mass flux versus concentration curve for 5 g Moringa.

6 Conclusions and Recommendations

The optimal dosage for $FeCl_3$ was 3 g and for Moringa was 5 g. Small dosages of Moringa was ineffective in treating the turbid water and required higher dosages to be added. On the other-hand, smaller dosages of $FeCl_3$ was able to treat the turbid water and explains why it is used commercially. However, the Moringa did produce the lowest turbidity between the two coagulants. Unfortunately the $FeCl_3$-Moringa coagulant did not produce the desired results as compared to the two other coagulants. A clear interface layer could not be detected and therefore the hindered settling velocity's using different dosages could not be determined. Using the optimal coagulant dosages, the actual cross-sectional area for the 3 g $FeCl_3$ was 38748 m^2 and for the 5 g Moringa was 6831 m^2.

To achieve better accuracy of the experimental results, more chemical material (specifically $FeCl_3$) must be provided to allow for repeatability. Also, more material is required to conduct more batch-settling tests at different dosages. This enables to make more conclusive results to conclude if there is a relationship between the amount of dosage added and measured turbidity. Finally, image comparison software can be used to see a clear interface layer for the $FeCl_3$-Moringa combination.

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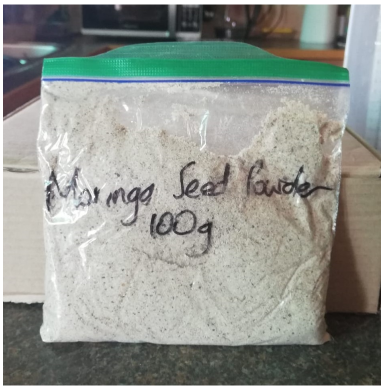
A Apparatus



(a) 100g of *Moringa Oleifera*.

(b) 20g of $FeCl_3$.

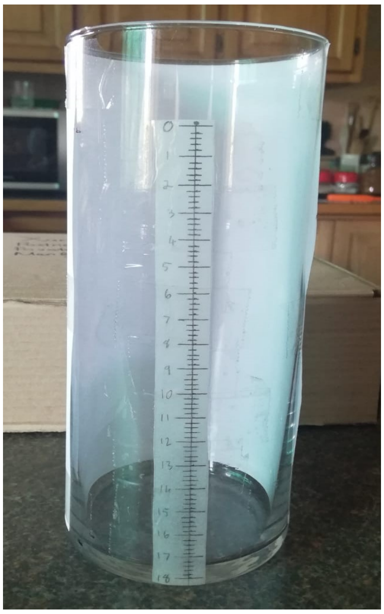
(c) 500g of Kaolin G3 clay.

Figure A.1: Experimental materials to be used.

(a) Electronic scale.

(b) Measuring glass and spoon for each material.

Figure A.2: Experimental equipment required to weigh materials.



(a) Cylindrical glass with marked measurements.

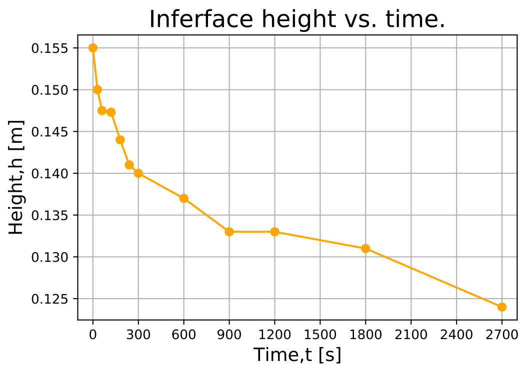
(b) Mixing rod.

(c) Secchi disk attached to rod.

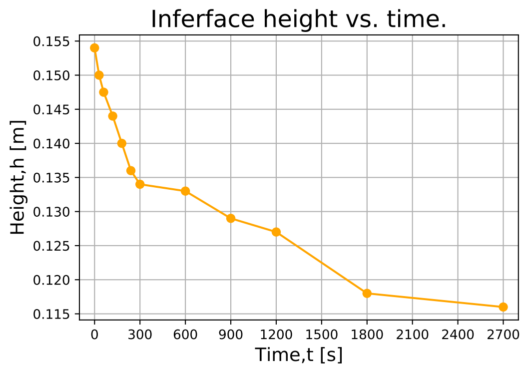
(d) 2000 ml measuring jug.

Figure A.3: Experimental equipment required to perform batch settling test.

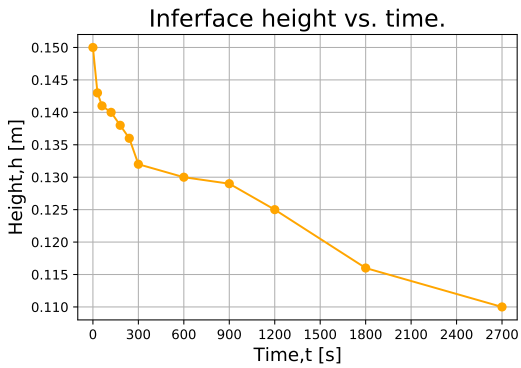
B Additional Experimental Results



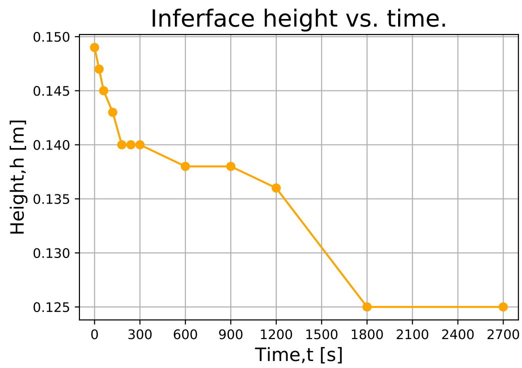
(a) 1 g $FeCl_3$ dosage.



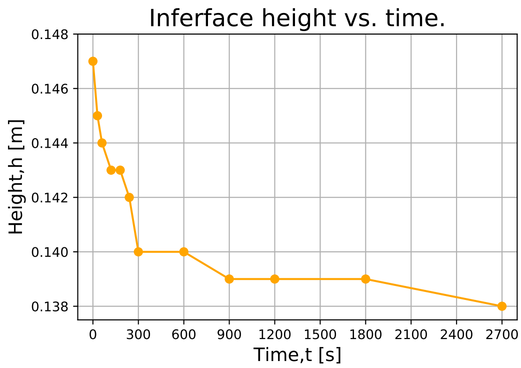
(b) 2 g $FeCl_3$ dosage.



(c) 3 g $FeCl_3$ dosage.

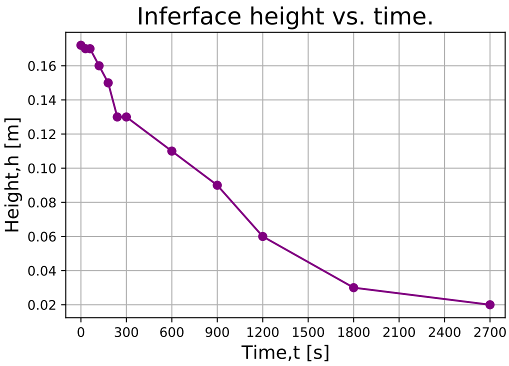


(d) 4 g $FeCl_3$ dosage.

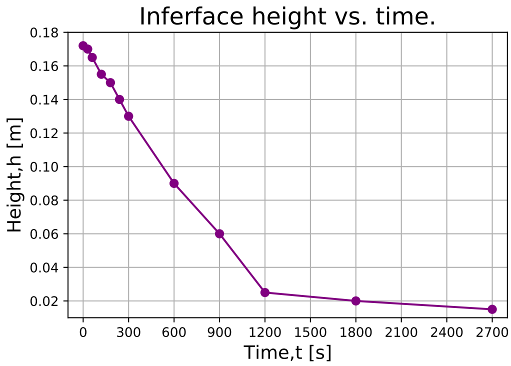


(e) 5 g $FeCl_3$ dosage.

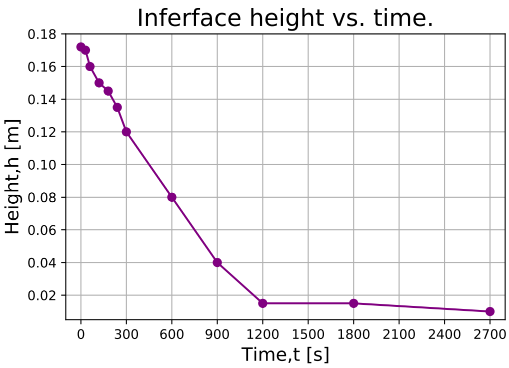
Figure B.4: Interface height versus time curves for all the different $FeCl_3$ coagulant dosages.



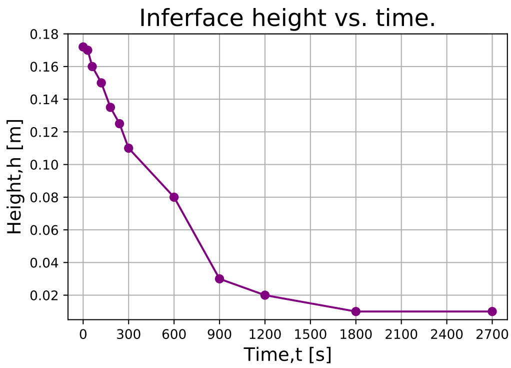
(a) 2.5 g Moringa Dosage.



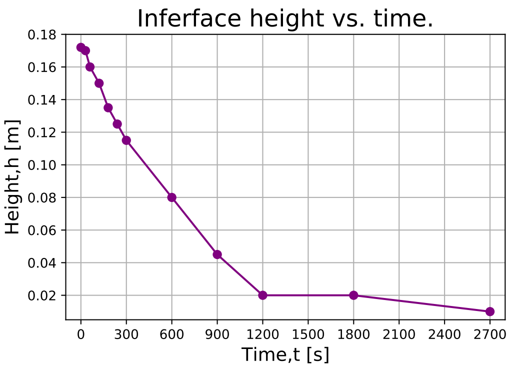
(b) 5 g Moringa Dosage.



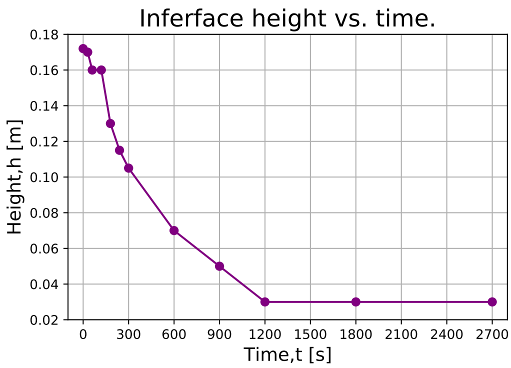
(c) 6 g Moringa Dosage.



(d) 7 g Moringa Dosage.



(e) 7.5 g Moringa Dosage.



(f) 10 g Moringa Dosage.

Figure B.5: Interface height versus time curves for all the different Moringa coagulant dosages.